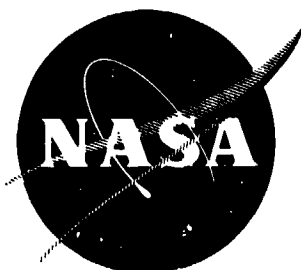


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NASA CR-135192
EDR 9132



STUDY OF TURBOPROP SYSTEMS

RELIABILITY AND MAINTENANCE COSTS

(NASA-CR-135192) STUDY OF TURBOPROP SYSTEMS
RELIABILITY AND MAINTENANCE COSTS Final
Report (Detroit Diesel Allison,
Indianapolis, Ind.) 304 p HC A14/MF A01

N80-14129

CSCI 21E G3/07

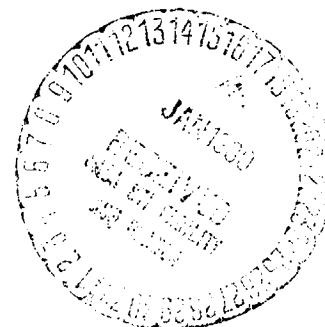
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Detroit Diesel Allison
Division of General Motors Corporation

prepared for



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center

Contract NAS 3-20057



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1.0 SUMMARY

A study of turboprop systems reliability and maintenance costs was conducted to achieve the following objectives:

- to identify and understand the overall and relative Reliability and Maintenance Costs (R&MC's) of the power section, gearbox, propeller, and accessories of past and current turboprop systems.
- to quantitatively project the R&MC improvements that could reasonably be expected to occur from these levels to those of new turboprop systems of the 1985 - 1990 IOC time period.

The scope of effort consisted of two tasks as follows:

Task I - To conduct an analysis of current and past turboprop propulsion systems to determine the principal factors that have affected their reliability and maintenance costs, and to establish an overall baseline comparison with current turbofans.

Task II - On the basis of the results of Task I and the incorporation of new design practices, new maintenance practices, and projected technology advances, determine quantitatively the R&MC improvement that could reasonably be expected to occur from the present turboprop levels to the 1985 - 1990 IOC level. Recommended actions and R&D programs to achieve the projected advances were to be defined.

In identifying and understanding the overall and relative R&MC's of past and current turboprop systems it is recognized that the real era of turboprop usage by the domestic airlines was in the early to mid 1960's. The Allison 501-D13 turboprop engines and the Aeronroducts 606 or Hamilton Standard 54H60 propellers were chosen for analysis of past systems, because of their wide usage on the Lockheed Electra and Convair 580 commercial airliners. The engines, main drive reduction gearboxes, and propellers were adaptations of military designs of the 1950's that were designed on the basis of a scheduled overhaul philosophy. For the airlines these scheduled overhauls occurred every 4000 to 9000 engine flight hours (TBO's). It was found that the cost of the scheduled overhauls accounted for 40 percent of the total maintenance cost of each of these major modules, and were the primary maintenance cost driver of the system. A very positive conclusion was drawn that a new turboprop system would embody the "On-Condition" philosophy that would eliminate scheduled overhauls. This philosophy would be facilitated by:

- Improved reliability where numbers of parts would be lowered and all parts would be designed for high durability and long life of 35,000 hours where possible.
- improved diagnostics utilizing newly developed automatic condition monitoring techniques for better fault detection and isolation.

In a turboprop system increased modularity was found to be an essential requirement. In past systems a failure in the propeller usually required complete removal of the propeller to get at the failed part. Modular propeller construction would be incorporated in a new system to minimize the amount of hardware removal while on the wing such as removal of damaged blades in pairs by pre-balanced replacements. The reduction gearbox of the old system incorporated three primary functions: the main drive reduction between the engine and propeller, a drive system for engine accessories, and a drive system for aircraft accessories. Problems in any one system usually required complete gearbox removal, including the propeller. A new system would make the main drive gearbox a simple system for just that purpose, incorporating high reliability in its bearings and gears for minimization of removal of either propeller or gearbox. The engine accessory drive system and aircraft accessory drive system would be individual modules, facilitating access and removal independently of the main drive reduction gear. Although the power section of the current system, a single spool core, is relatively simple it was found that increased modularity and easier access to the power section in the nacelle was a requirement. The clamshell approach to nacelle design was adopted for the new system with a built-in hoist system for support and lowering of individual major modules for easier access to power section sub-modules, engine and aircraft accessories and drives, and the control system.

Simplification of the control system was found necessary. The current system is a relatively complex hydro-mechanical system incorporating a number of components that were subject to unjustified removals. The new control would be an integrated system controlling the functions of the power section and advanced propeller. It would incorporate a full authority digital electronic controller, with a self-check capability to detect and provide indication of the occurrence of a malfunction of any of the separate control system components.

Certain inherent features on early turboprops were found to be significant cost drivers such as the rear compressor bearing in the engine, and blade heaters on the propeller. Bearing problems such as was encountered can be handled with current and future design criteria. Blade heaters are susceptible to FOD and erosion and improved concepts must be developed to lower the frequency of heater failures.

In addition to establishing the reasons for, or the breakdown of current and past turboprop maintenance costs, comparisons were also drawn with the JT8D turbofan. Scaling was done to equate the two systems to produce the same thrust at 0.8M at 35,000 feet altitude, and to operate them at the same duty cycle. Costs per flight hour of the turboprop elements of propeller and gearbox were higher than those of the turbofan elements of fan and reverser (\$7.94 vs \$3.36). However there were also major differences in the engine core, where the older technology turboprop core maintenance costs were nearly 70 percent higher than those of the turbofan (\$45.24 vs \$27.11). As a result, total maintenance cost per engine flight hour of the turboprop was 75% worse than that of the JT8D. However in projecting the maintenance cost of an advanced turboprop that incorporated the recommended reliability and maintenance characteristics, the maintenance cost of the advanced propeller (Prop-Fan) and gearbox was established at \$0.73 versus \$2.40/EFH for the fan and reverser of an advanced turbofan. The core costs of the advanced turboprop and advanced turbofan were comparable. The estimated maintenance costs of both the advanced turboprop and advanced turbofan were less than the JT8D. The reductions were largely due to the elimination of scheduled overhauls. The conclusion was that an advanced turboprop and an advanced turbofan, using similar cores, will have very competitive maintenance costs per flight hour. Maintenance costs do not appear to be a valid barrier against possible airline use of future turboprops.

2.0 INTRODUCTION

The National Aeronautics and Space Administration (NASA) has sponsored studies by Pratt and Whitney and General Electric that would lead toward methods of reducing energy consumption in turbofan engines. These studies have included improvements in conventional turbofan systems, and the investigation of unconventional engines. Concurrently Boeing, Douglas, and Lockheed have been running studies (RECAT), also sponsored by NASA, toward improvements in aircraft systems and operational procedures that would reduce energy consumption. The improved offerings of P&W and GE have been included in the latter studies. One of the most promising concepts is an advanced turboprop having an advanced propeller capable of 80% efficiency at 0.8M, 35,000 feet altitude. The performance and noise characteristics of this advanced propeller concept is currently under investigation at NASA. Up to 30% reduction in fuel consumption compared to current turbofans and 15% compared to advanced high bypass ratio turbofans will be possible with the advanced turboprop.

Based upon past experience, turboprop maintenance cost was generally considered high compared to first generation turbofans. However, the turboprops were older technology, and concerted efforts to reduce turboprop maintenance costs were not made since the mid 1960's when most turboprop users were phasing out their equipment. An appraisal of maintenance costs for new advanced turboprop systems was necessary to determine the net effect of new turboprop systems on Direct Operating Costs (DOC's) in comparison to new turbofan systems. In addition, passenger and public preference prevailed against the turboprop compared to the turbofan. Therefore NASA contracted with Detroit Diesel Allison (DDA), Contract NAS3-20057, to study past and current turboprop systems to determine their maintenance costs on a flight hour basis, and to determine an understanding of where the maintenance costs were incurred, and to make recommendations where improvements could be made. Finally, a projection was to be made as to what the maintenance cost per flight hour would be for an advanced turboprop system of the 1985 - 1990's. Hamilton Standard (HS) was subcontracted by DDA to do the propeller portion of the study and to assist in the conceptual aspects of the complete advanced turboprop propulsion system.

3.0 TASK I - COLLECTION, PREPARATION, AND ANALYSIS OF ACTUAL TURBOPROP PROPULSION RELIABILITY AND MAINTENANCE COSTS

3.1 Selection of Turboprop Propulsion System for Analysis

The subject of this overall study is an advanced turboprop propulsion system that is primarily intended for use by airlines requiring aircraft that can fly at high subsonic speeds of 0.7 to 0.8 Mach number. In this category of aircraft are the future replacements for such aircraft as the B707, B727, B737, B747, DC-8, DC-9, DC-10, and L-1011. All of these aircraft require engines in the high thrust region of 14,000 to 50,000 lbs.

For the majority of the airlines that would use this type of aircraft, their era of turboprop usage was in the mid 1960's and their association of turboprop maintenance costs with those of turbofans would result from their turboprop experience of that time. Table 3.1-I shows engine and propeller flight hours for the years 1965 through 1975 as reported to the CAB by certificated route carriers. The turboprop powered aircraft that were principally used by the major airlines in their "turboprop era" were the Lockheed Electra, Convair CV580, and the Viscount. The Electra and CV580 were powered by the Detroit Diesel Allison Model 501-D13 engines and either Aeroproducts Model 606 or Hamilton Standard Model 54H60 propellers. The Viscount was powered by the Rolls-Royce Dart and Rotol propellers. The largest and most heavily used system even through 1975 was the 501/606/54H60. Because of this experience, together with its military usage in the C130, P3, and E2/C2 aircraft, the 501/606/54H60 turboprop propulsion systems is generally recognized as the most significant high power turboprop system used in the western world. For these reasons, the 501-D13 and its propeller was selected as the most representative turboprop system upon which could be based the projection for future large advanced systems. The 501-D13 engine, including the main drive reduction gear assembly, is shown in Figure 3.1-1. Figures 3.1-2 and 3.1-3 show assembly diagrams of the Aeroproducts 606 and the Hamilton Standard 54H60 propellers, respectively. Table 3.1-II gives the ratings of the 501-D13.

3.2 Data Sources

During the course of the study the following four sources of data were found the most useful for determining removal rates, removal reasons, maintenance schedules, and repair and overhaul costs:

Table 3.1-1
TURBOPROP USAGE BY CERTIFICATED ROUTE CARRIERS

| POWERPLANT MODEL | ESHP | AIRCRAFT | PROPELLER MODEL | CY 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 |
|------------------------------|------|----------------|--|---------|------|------|------|------|------|------|------|------|------|------|
| ALLISON 501-D13 | 3750 | L1188 ELECTRA | A6441FN-606 A64460-B1 A6441FN-606A | 1188 | 1040 | 1092 | 688 | 428 | 80 | 216 | 196 | 212 | 164 | 140 |
| ALLISON 501-D22 | 4050 | CV580 CONVAIRE | A6441FN-606A | 64 | 150 | 274 | 405 | 480 | 472 | 454 | 458 | 408 | 334 | 286 |
| TOTAL 501-D13/D22 HOURS | | L3822 HERCULES | 50460-117 | 1252 | 1206 | 1438 | 1186 | 996 | 632 | 794 | 798 | 810 | 650 | 586 |
| ROLLS-ROYCE DART | 1600 | V700 VISCOUNT | R-148/4-20-4/21E | 384 | 272 | 252 | 176 | 16 | 16 | | | | | |
| 1990 | | V800 VISCOUNT | R-179/4-20-4/23 | 132 | 108 | 20 | | | | | | | | |
| 2750 | | CV600 CONVAIRE | R-245/4-40-4.5/13 | | 66 | 168 | 190 | 124 | 102 | 88 | 78 | 80 | 58 | 28 |
| 3000 | | P27 FRIENDSHIP | R-175/4-30-4/13E | 240 | 302 | 242 | 216 | 176 | 118 | 96 | 72 | 90 | 46 | 34 |
| 3000 | | PH227 | R-193/4-30-4/50 | | 12 | 190 | 272 | 250 | 208 | 166 | 140 | 106 | 124 | 110 |
| 3000 | | YS 11 | R-209/4-40-4.5/2 | 776 | 760 | 880 | 872 | 46 | 100 | 162 | 104 | 100 | 96 | 100 |
| TOTAL ROLLS-ROYCE DART HOURS | | | | | | | | | 536 | 452 | 294 | 376 | 324 | 274 |
| ROLLS-ROYCE TYNE | 5720 | CL 440 | 4/7000/6 | 300 | 232 | 176 | 112 | 20 | | | | | | |
| PRATT & WHITNEY PT6 | 600 | 899 BEECH | HC-80TN-28 | | | | | | | 14 | | | | |
| 600 | | DHC-6 | HC-80TN-20 | | | | | | | | | | | |
| TOTAL PT6 HOURS | | | | | | | 10 | 12 | 22 | 28 | 28 | 26 | 26 | 58 |

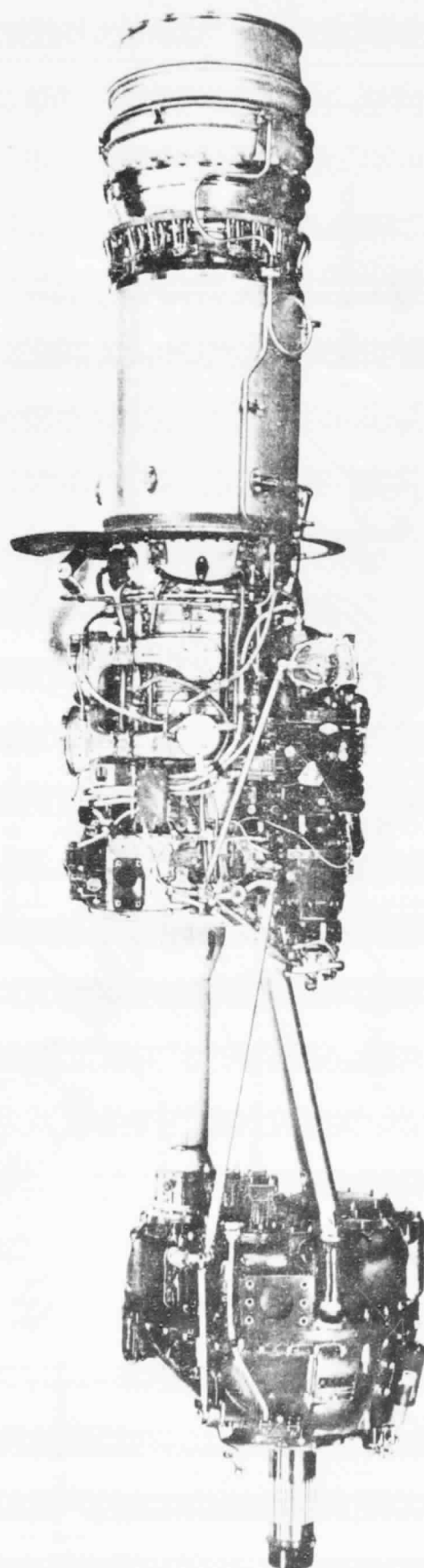
POWER SECTION

TORQUEMETER ASSEMBLY
AND TIE STRUT

COMPRESSOR
ASSEMBLY

COMBUSTION
ASSEMBLY

TURBINE
ASSEMBLY



REDUCTION GEAR ASSEMBLY

ACCESSORIES DRIVE
HOUSING ASSEMBLY

Figure 3.1-1. Detroit Diesel Allison model 501-D13 turboprop engine.

MAJOR ASSEMBLIES

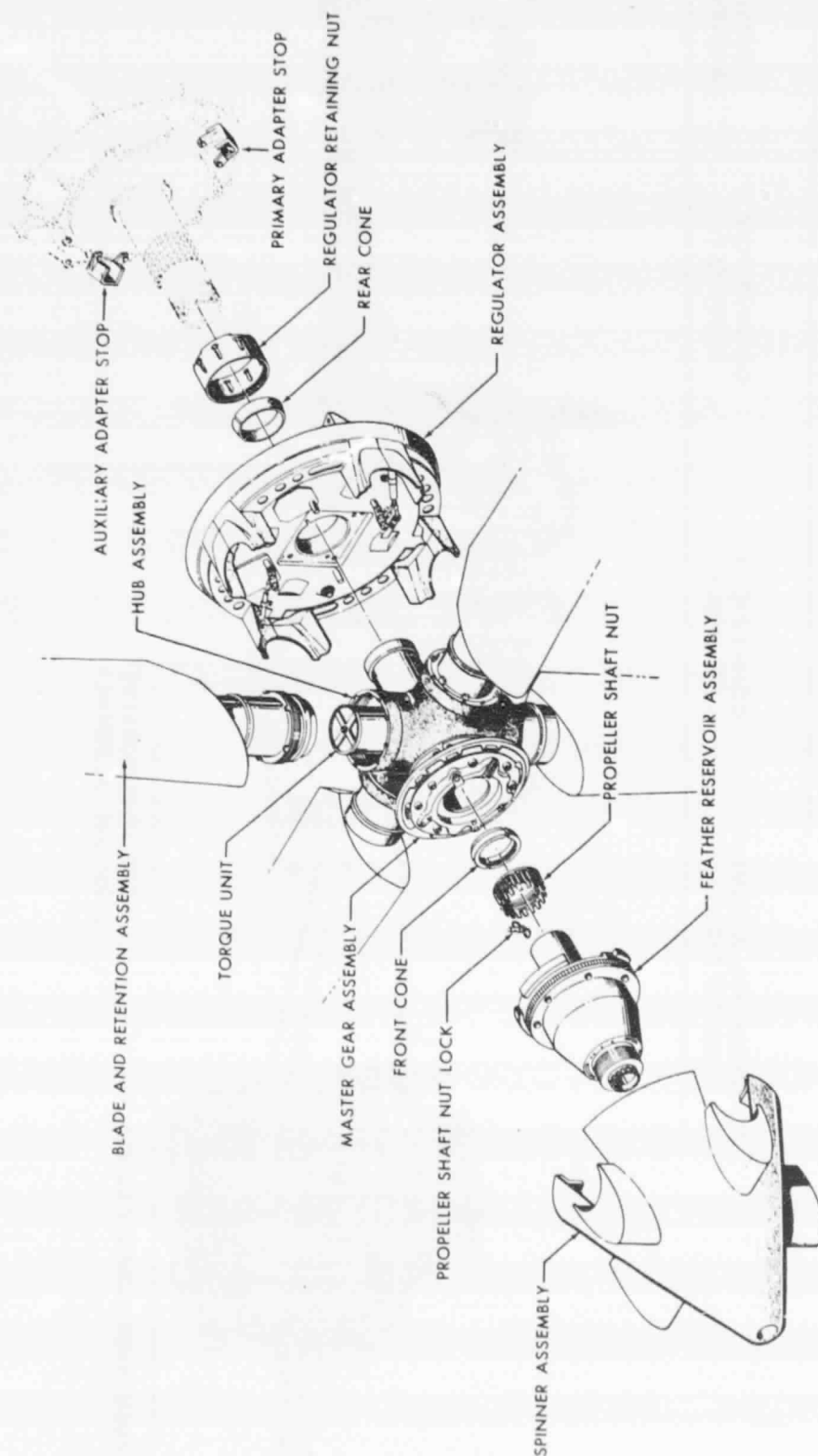


Figure 3.1-2. Diagrammatic assembly of Aero products 606 propeller.

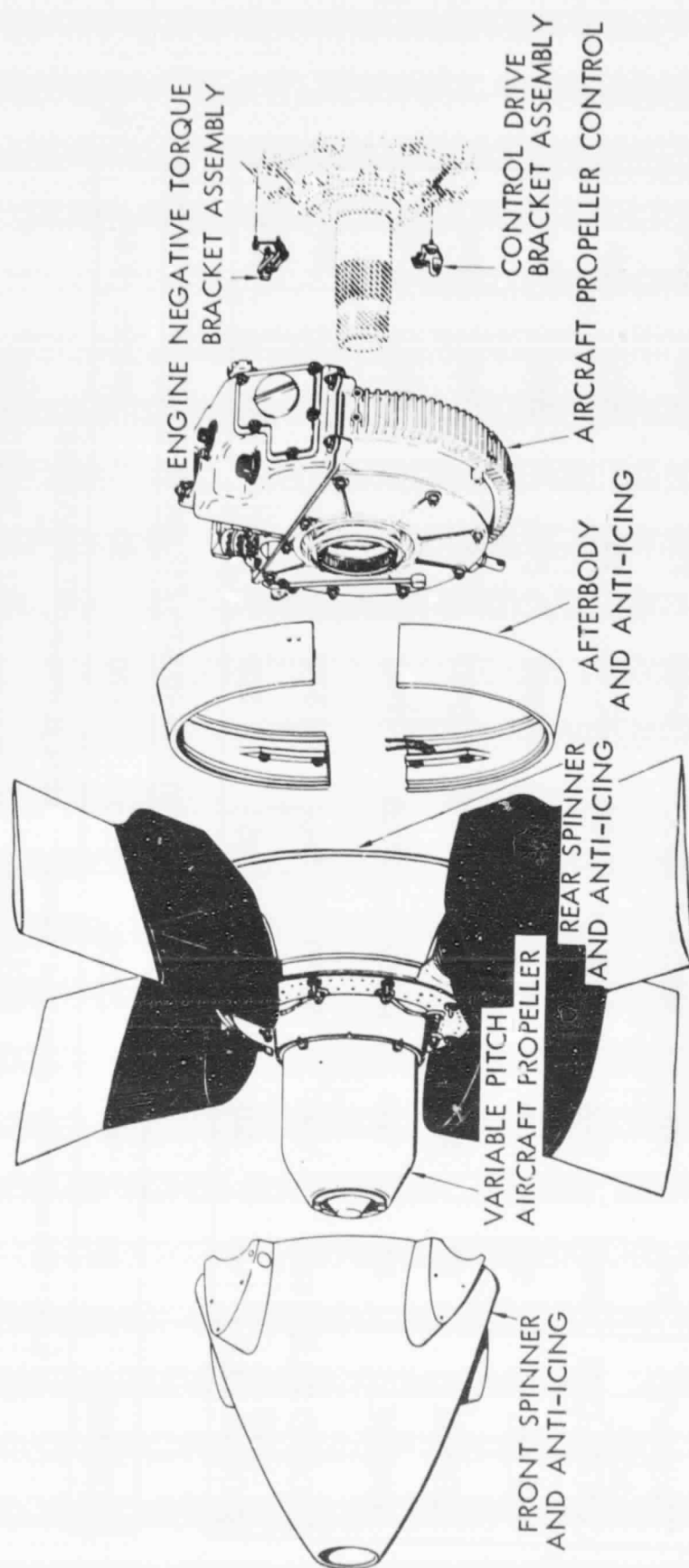


Figure 3.1-3. Diagrammatic assembly of Hamilton Standard 54H60 propeller.

TABLE 3.1-II

MODEL 501-D13 RATINGS

| RATINGS | %MRT | TURBINE INLET °C | RPM | ESH | PROP SHP | JET THRUST | STANDARD DAY | |
|--------------------|------|---------------------|-------|------|-------------|---------------|--|--------|
| | | | | | | | FUEL CONSUMPTION ESFC LB/HR/ESHP | LBS/HR |
| TAKE-OFF | 100 | 971 | 13820 | 3750 | 3460 | 726 | 543 | 2036 |
| MAX. CONTINUOUS | 96.9 | 932 | 13820 | 3420 | 3138 | 705 | .553 | 1891 |
| CLIMB | 94 | 895 | 13820 | 3105 | 2831 | 684 | .568 | 1764 |
| CRUISE | 90 | 847 | 13820 | 2700 | 2437 | 657 | .592 | 1598 |
| CRUISE | 84 | 768 | 13820 | 2025 | 1780 | 613 | .665 | 1345 |
| GROUND IDLE | 69.6 | 593 | 13500 | 585 | 370 | 540 | 1.4 | 819 |
| LOW GROUND IDLE | 70.8 | 610 | 10100 | 315 | 200 | 285 | 2.0 | 633 |

STANDARD DAY- 352 KNOTS-20,000 FT.

| | | | | | | | | |
|--------|----|-----|-------|------|------|-----|--------|------|
| CRUISE | 90 | 847 | 13820 | 2150 | 1970 | 150 | 484±2% | 1050 |
|--------|----|-----|-------|------|------|-----|--------|------|

%MRT = % OF MAX. RATED TEMP.(TIT) IN °RANKINE STATIC ESHP = SHP + $\frac{\text{JET THRUST (LBS)}}{2.5}$

USING EMS-64C KEROSENE WITH 18,600 BTU/LB FLIGHT ESHP = SHP + $\frac{\text{NET JET THRUST X SPEED}}{325.5 \times 80\%}$

REDUCTION GEAR RATIO = 13.54:1 80% PROP. EFFICIENCY

PROPELLER DIAMETER = 13.5 FT.

- DDA reliability department records
- CAB Form 41
- Repair facilities
- Airline records

3.2.1 DDA Reliability Department Records

DDA developed an extensive data bank of reliability statistics on commercial operation of the 501-D13 engine and 606 propeller during the 1960's. This data was gathered from all operators of the L188 Electra and the CV580 Convair. A summary of the data was published each month, which included the following:

- Engine and propeller flight hours
- Major unit premature removals, including inherent (primarily propulsion system equipment caused) and non-inherent (primarily not caused by the propulsion system).
- Cause for each premature removal
- Rates of premature removals per 1000 hours
- Time expired removals

Figure 3.2.1-1 shows a matrix of calendar year versus airline for which this type of data was available for the Electra. In the earlier years, the data was reported separately for domestic and non-domestic airlines. Then the Unit Exchange program was started, and the data was reported separately for Unit Exchange and Non-Unit Exchange operators. The Unit Exchange program on the Electra was a repair and overhaul operation that DDA conducted for American, Braniff, National, Western, and Pacific Southwest Airlines. In this program engines and propellers were not repaired or overhauled by the participating airlines, but the removals were sent to DDA for this work. Replacement engines and propellers were sent to the participating airlines upon receipt of removed engines and propellers. In addition, airline maintenance actions to service, remove, and install engines and propellers were warranted on a man-hour basis. Under this program DDA had very close cognizance of

| Y | AMERICAN | BRANIFF | NATIONAL | WESTERN | PSA | EASTERN | NORTHWEST | FRONTIER (CV580) | VARIG | ANSETT | GARUDA | KLM | QANTAS | TRANS AUSTRALIA | AIR NEW ZEALAND | TASMAN | CATHAY PACIFIC | AVENSA |
|-------|----------|---------|----------|---------|-----|---------|-----------|------------------|-------|--------|--------|-----|--------|-----------------|-----------------|--------|----------------|--------|
| 1962 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | | | 1 | 4 | | 4 | | 4 | 4 | 4 | |
| 1963 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | | 4 | 4 | 4 | |
| 1964 | 1,2 | 1,2 | 1,2 | 1,2,3 | 2,3 | 2,3 | 2 | 3,4 | 3,4 | 3,4 | 3,4 | 3,4 | 3,4 | | 3,4 | 3,4 | | |
| 1965 | 1 | 1 | 1 | 1,3 | 3 | 3 | | 3 | 3 | 3 | 3 | 3 | 3 | | 3 | 3 | | |
| 1966 | 1 | 1 | 1 | 3 | 3 | 3 | | 3 | 3 | 3 | 3 | 3 | 3 | | 3 | 3 | | |
| 1967 | 1 | 1 | 1 | 3 | 3 | 3 | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | | | |
| 1968 | 1 | 1 | 1 | | 3 | | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | | | | |
| •1969 | 1 | 1 | 1 | | 3 | | | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | | | |

- 1 - UNIT EXCHANGE
- 2 - DOMESTIC AIRLINES
- 3 - NON-UNIT EXCHANGE
- 4 - NON-DOMESTIC

•RECORDS DO NOT COVER THE COMPLETE YEAR.

Figure 3.2.1-1. Reliability Department Records - L188 Electra and CV580 Airplanes.

the required maintenance for the turboprop system on the Electra. Figure 3.2.1-2 is a similar matrix showing data availability for the Convair CV580 airplane. Operation of the CV580 by scheduled airlines did not begin until CY 1964.

Tables 3.2.1-I through 3.2.1-X are extracted from the January 1968 monthly summary of engine and propeller removals for Unit Exchange Airlines. The data is presented as an example of that available in the DDA Reliability Department records of Figures 3.2.1-1 and 3.2.1-2. Removal records are shown by month for CY 1966 and 1967. Engine and propeller flight hours are shown in Table 3.2.1-I. The engine's major modules were the hot section (turbine and combustion section), the cold section (compressor), the main drive reduction gear, and the torque meter/shaft between the power section and reduction gear. Premature removal rates for these major modules are shown in Table 3.2.1-II in addition to the time expired removals for the hot and cold sections. The reduction gear and torque meter were included with the cold section for time expired removals. Tables 3.2.1-III through 3.2.1-VI show the primary reason for each premature removal that was inherently engine caused. Table 3.2.1-VII shows the causes of non-inherent premature engine removals. Major modules of the propeller were hub, blades, and regulator. Tables 3.2.1-VIII and 3.2.1-IX show premature removals and their reasons for the propeller modules. Table 3.2.1-X gives the propeller time expiration and non-inherent removals.

3.2.1.1 HS Review of DDA Reliability Data

HS reviewed the data prepared by the DDA Reliability Department covering propeller performance during the period 1960 thru 1969. CV580 Scheduled Airline data and Electra Domestic Airline and Unit Exchange Airline portions of these reports were reviewed to establish premature removal rates for the propeller and regulator hardware. The results have been summarized in Figures 3.2.1.1-1 and 3.2.1.1-2 for the DDA CV580 and Electra propellers respectively.

3.2.1.2 Propeller Cost Data

During the course of the study, it was found that propeller maintenance costs on a cost per flight hour basis were difficult to obtain. DDA had a limited amount of cost data as a result of the Unit Exchange program. This data is summarized in Table 3.2.1.2-I.

| CY | SCHEDULED AIRLINES | | | | | | | | | | PRIVATE OPERATORS | | | | | | | | | | | | | | | | | |
|------|--------------------|--------|-----------|--------------|---------------|------|------|------------|----------|-----|-------------------|----------|-----|-------|-------------------|-------|--------------------|-----------|--------------------|-----------|-------|----------------------|---------|---------|---------|---------|---------|---------|
| | FRONTIER | AVENSA | ALLEGHENY | LAKE CENTRAL | NORTH CENTRAL | GMTS | ESSO | HUMBLE OIL | FORD OIL | FAA | GULF OIL | PAC AERO | ESC | SCAIF | JOHNSON & JOHNSON | BOYER | EAST. CANADA INDS. | BETHLEHEM | GREAT LAKES CARBON | ALLEGHENY | ESSEX | 80TH AIR TRANS. WING | FAUNIER | FAUNIER | FAUNIER | FAUNIER | FAUNIER | FAUNIER |
| 1960 | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | |
| 1961 | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | |
| 1962 | | | | | | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | | |
| 1963 | | | | | | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | | |
| 1964 | X | | | | | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | | |
| 1965 | X | X | | | | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | | |
| 1966 | X | X | X | | | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | | |
| 1967 | X | X | X | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | | |
| 1968 | X | X | X | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | | |
| 1969 | X | X | X | X | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | | | | | | | |

Figure 3.2.1-2. Reliability Department Records - Convair CV580 Airplane

| | MONTHLY ENGINE FLIGHT HOURS | ACCUMULATED ENGINE FLIGHT HOURS | AIRCRAFT IN SERVICE | AIRCRAFT UTILIZATION HRS. PER DAY |
|------|-----------------------------------|---------------------------------------|------------------------|---|
| 1965 | | | | |
| YEAR | 652,360 | 3,794,256 | 62 | |
| 1966 | | | | |
| JAN | 55,628 | 3,849,884 | 62 | 7.2 |
| FEB | 49,302 | 3,899,186 | 62 | 7.1 |
| MAR | 54,380 | 3,953,566 | 62 | 7.1 |
| APR | 54,056 | 4,007,622 | 62 | 7.3 |
| MAY | 56,348 | 4,063,970 | 62 | 7.3 |
| JUN | 53,024 | 4,116,994 | 62 | 7.1 |
| JUL | 41,216 * | 4,158,210 | 62 * | 6.8 |
| AUG | 44,660 * | 4,202,870 | 62 * | 6.9 |
| SEP | 52,172 | 4,255,042 | 62 | 7.0 |
| OCT | 53,576 | 4,308,618 | 63 | 6.9 |
| NOV | 51,568 | 4,360,186 | 62 | 6.9 |
| DEC | 51,220 | 4,411,406 | 61 | 6.8 |
| 1967 | | | | |
| JAN | 51,368 | 4,462,774 | 61 | 6.8 |
| FEB | 46,772 | 4,509,546 | 61 | 6.8 |
| MAR | 53,244 | 4,562,790 | 61 | 7.0 |
| APR | 54,040 | 4,616,830 | 61 | 7.4 |
| MAY | 56,912 | 4,673,742 | 61 | 7.5 |
| JUN | 54,200 | 4,727,942 | 61 | 7.4 |
| JUL | 54,548 | 4,782,490 | 61 | 7.2 |
| AUG | 56,276 | 4,838,766 | 61 | 7.4 |
| SEP | 52,368 | 4,891,134 | 60 | 7.3 |
| OCT | 52,336 | 4,943,470 | 60 | 7.0 |
| NOV | 48,060 | 4,991,530 | 58 | 6.9 |
| DEC | 49,140 | 5,040,670 | 56 | 7.1 |

* National Airlines' 17 aircraft flew only 18 days in July and August because of strikes.

Table 3.2.1-I. 501-D13 Engine and 606 Propeller Flight Hours,
Unit Exchange Airlines

JANUARY 1968

1966

1967

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|--|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| TIME EXPIRATION REMOVALS (ENGINE) | 4 | 5 | 9 | 0 | 5 | 7 | 3 | 4 | 3 | 2 | 3 | 2 | - | 4 | 3 | 2 | 4 | 2 | 3 | 2 | 7 | 3 | 3 | 1 |
| TIME EXPIRATION REMOVALS (TURBINE) | 13 | 7 | 6 | 0 | 13 | 9 | 9 | 6 | 7 | 11 | 11 | 4 | 2 | 7 | 12 | 15 | 3 | 8 | 3 | 10 | 7 | 10 | 15 | 3 |
| ENGINE RESPONSIBLE REMOVALS | | | | | | | | | | | | | | | | | | | | | | | | |
| POWER SECTION LESS TURBINE REMOVALS | | | | | | | | | | | | | | | | | | | | | | | | |
| Removals Per 1000 Hours | .14 | .12 | .09 | .11 | .10 | .17 | .17 | .09 | .08 | .19 | .07 | .15 | .21 | .30 | .13 | .13 | .05 | .20 | .07 | .14 | .06 | .09 | .13 | .08 |
| TURBINE REMOVALS | 1 | 4 | - | 4 | 4 | 2 | 2 | 2 | 6 | 1 | 9 | 4 | 3 | 4 | 3 | 6 | 3 | 2 | 3 | 1 | 3 | 3 | 2 | 4 |
| Removals Per 1000 Hours | .02 | .08 | - | .08 | .07 | .04 | .05 | .04 | .11 | .02 | .18 | .08 | .06 | .09 | .06 | .11 | .05 | .04 | .06 | .02 | .06 | .06 | .04 | .08 |
| SECTION GEAR REMOVALS | 7 | 15 | 12 | 12 | 5 | 12 | 10 | 7 | 15 | 14 | 9 | 16 | 18 | 11 | 13 | 8 | 21 | 14 | 11 | 15 | 14 | 13 | 6 | 13 |
| Removals Per 1000 Hours | .12 | .31 | .22 | .22 | .09 | .22 | .24 | .16 | .29 | .26 | .18 | .35 | .35 | .23 | .24 | .15 | .37 | .26 | .20 | .27 | .26 | .25 | .12 | .25 |
| TURBOCHARGER REMOVALS | 2 | 2 | 3 | 6 | 1 | 2 | 1 | - | 3 | 1 | 1 | 3 | 3 | 3 | - | - | - | 1 | 2 | - | 3 | 3 | 2 | - |
| Removals Per 1000 Hours | .04 | .04 | .06 | .11 | .02 | .04 | .03 | - | .04 | .02 | .02 | .06 | .06 | .06 | - | - | - | .02 | .04 | - | .06 | .06 | .04 | - |
| SWP-TOTAL | 18 | 27 | 20 | 28 | 16 | 25 | 20 | 13 | 28 | 26 | 23 | 33 | 35 | 32 | 23 | 21 | 27 | 28 | 28 | 24 | 23 | 24 | 16 | 21 |
| Removals Per 1000 Hours | .32 | .55 | .37 | .52 | .28 | .47 | .49 | .29 | .54 | .49 | .45 | .64 | .68 | .68 | .43 | .39 | .47 | .52 | .37 | .43 | .44 | .46 | .33 | .43 |
| NON-ENGINE RESPONSIBLE REMOVALS | 14 | 12 | 9 | 9 | 15 | 12 | 9 | 9 | 18 | 12 | 14 | 13 | 14 | 12 | 17 | 22 | 13 | 21 | 15 | 15 | 18 | 17 | 12 | 12 |
| UNCLASSIFIED REMOVALS - ANTICIPATED NON-ENGINE RESPONSIBLE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | 2 | 5 | 3 |
| TOTAL REMOVALS | 49 | 51 | 44 | 45 | 49 | 53 | 41 | 32 | 56 | 51 | 51 | 52 | 51 | 55 | 55 | 40 | 47 | 59 | 41 | 52 | 56 | 56 | 51 | 40 |
| FROM 1967 UNIT EXCHANGE 504-013 AND 645 | | | | | | | | | | | | | | | | | | | | | | | | |
| JANUARY 1968 | | | | | | | | | | | | | | | | | | | | | | | | |

Table 5.2.1-II. Summary of Major Engine Unit Removals

STOPS!

**Labyrinth Rotating - Compressor Rear
Extension Shaft "G" Ring**

WILLIAMS

**Fuel Pump Drive
Front Compressor
Rear Compressor
Accessory Drive Shaft
Center Act. Drive Gear
Extension Shaft**

CONTROL SYSTEMS

Blade - 3rd Stage
Vene Assy. - 1st Stage
Bolt - Wheel Flt
Blade - 2nd Stage
Vene Assy. - 3rd Stage
Vene Assy. - 2nd Stage
Blade - 6th Stage
Blade - 10th Stage

12/24/16
12/24/16
12/24/16

Understand

DIFFER ASSEMBLY. COMPLETION
GEAR ASSEMBLY. INCOMPLETION DURING
LATER ASSEMBLY. COMPLETION
POLICE ASSEMBLY. PTL
PRIVATELY FAILURE COMPLETED
CUT. COMPLETION DURING REPAIRING
CUT. INCOMPLETELY. CYCLES

12-05541-169 2C-XPLS

Failed Ignition
Oil Leak
Low Oil Pressure
High Oil Pressure
Metal on Mag. Plug
Bounced
Low Fuel

Total

9061 Avenue
905 Guy (10-105 Exchange Jkt)
2002 on road

20

JANUARY 1969

Table 3.2.1-III. Power Section (Less Turbine) Premature Removals

1967

ENGINE RESPONSIBLE

1966

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| REASON FOR REMOVAL - CLASSIFIED | | | | | | | | | | | | | | | | | | | | | | | | |
| SEALS: | | | | | | | | | | | | | | | | | | | | | | | | |
| BEARINGS: | | | | | | | | | | | | | | | | | | | | | | | | |
| Rear Turbine | | | | 2 | 3 | | | | 2 | | 4 | 1 | | 2 | | 2 | 1 | 2 | | | | | 1 | 3 |
| TURBINE: | | | | | | | | | | | | | | | | | | | | | | | | |
| Shaft Assy. Turbine | | | | | | | | | | | | | | | | | | | | | | | | |
| Spacer - 3rd to 4th | | | | | | | | | | | | | | | | | | | | | | | | |
| Blade - 1st Stage | | | | | | | | | | | | | | | | | | | | | | | | |
| Rotor Assy. | | | | | | | | | | | | | | | | | | | | | | | | |
| Vane Assy. - 1st Stage | | | | | | | | | | | | | | | | | | | | | | | | |
| Wheel - 3rd Stage | | | | | | | | | | | | | | | | | | | | | | | | |
| Vane Assy. - 3rd Stage | | | | | | | | | | | | | | | | | | | | | | | | |
| SCAVENGE PUMPS: | | | | | | | | | | | | | | | | | | | | | | | | |
| Front Turbine | | | | | | | | | | | | | | | | | | | | | | | | |
| Shaftgear - Drive | | | | | | | | | | | | | | | | | | | | | | | | |
| Pin - Cotter | | | | | | | | | | | | | | | | | | | | | | | | |
| Rear Turbine | | | | | | | | | | | | | | | | | | | | | | | | |
| Seal "O" Ring | | | | | | | | | | | | | | | | | | | | | | | | |
| Bushing - Gearshaft | | | | | | | | | | | | | | | | | | | | | | | | |
| SUPPORT ASSEMBLY - REAR TURBINE BEARING | | | | | | | | | | | | | | | | | | | | | | | | |
| CAGE ASSEMBLY - FRONT TURBINE BEARING | | | | | | | | | | | | | | | | | | | | | | | | |
| BOLT - FLANGE FRONT TURBINE BEARINGS | | | | | | | | | | | | | | | | | | | | | | | | |
| PRIMARY FAILURE UNDETERMINED | | | | | | | | | | | | | | | | | | | | | | | | |
| CASING ASSY. - TURBINE INLET | | | | | | | | | | | | | | | | | | | | | | | | |
| SPACER - TURB. REAR BNG. SEAL | | | | | | | | | | | | | | | | | | | | | | | | |
| RETAINING JET - REAR TURB. BNG. SUPPORT | | | | | | | | | | | | | | | | | | | | | | | | |
| SEAL RING - FR. TURBINE BNG. CAGE | | | | | | | | | | | | | | | | | | | | | | | | |
| UNCLASSIFIED REMOVALS | | | | | | | | | | | | | | | | | | | | | | | | |
| Failed Unknown | | | | | | | | | | | | | | | | | | | | | | | | |
| Vibration | | | | | | | | | | | | | | | | | | | | | | | | |
| Oil Leak | | | | | | | | | | | | | | | | | | | | | | | | |
| Damaged | | | | | | | | | | | | | | | | | | | | | | | | |
| TOTAL | 1 | 4 | 0 | 4 | 4 | 2 | 2 | 2 | 6 | 1 | 9 | 4 | 3 | 4 | 3 | 6 | 3 | 2 | 3 | 1 | 1 | 4 | 3 | 4 |

FORM NO. 2467 UNIT EXCHANGE 501-D13 AND 606 JANUARY 1968

Table 3.2.1-IV. Turbine Section Premature Removals

REASON FOR REMOVAL - CLASSIFIED

BEARINGS:

Planet Gear and Bearing Assembly
 Front Pinion
 Rear Pinion
 Starter Shaft
 Hydraulic Pump Idler Gear
 Oil Pump Drive Idler
 Main Idler Gear
 Main Drive Gear

SEALS:

Prop Brake
 Prop Shaft Bearing
 NIS Plunger

GEARS:

Main Drive
 Alternator Drive
 Hydraulic Pump Idler Drive
 Hydraulic Pump Idler
 Hydraulic Pump Drive
 Starter
 Main Idler

SHAFT ASSEMBLY - HYDRAULIC PUMP DRIVE

WASHER - OIL PUMP DRIVE GEAR
 CAGE - OIL PUMP IDLER GEAR BEARING
 PRIMARY FAILURE UNDETERMINED

SHAFT - STARTER

SHAFT ASSEMBLY - ALTERNATOR DRIVE

DIAPHRAGM - R/G MAIN

CASE ASSEMBLY - R/G STUDDING - REAR

FLANGE - CARRIER OIL DELIVERY

PROPELLER BEARING ASSEMBLY

PUMP - SCAVENGE OIL MAIN

JOURNAL - OIL PUMP DRIVE IDLER

BOLT - RING GEAR

NUT - PROP SHAFT THRUST BRG.

FLANGE - STARTER DRIVE BRG.

SPACER - UPPER HOULT

COUPLING - HELICAL SPLINE

CASE ASSEMBLY - R/G FRONT

BUSHING - SHAFT GEAR SPUR PINION

LOCK - TAB - RING GEAR

RING - MAIN DRIVE DAMPENER

PUMP ASSY. - MAIN OIL

CAGE - NOSE BEARING

UNCLASSIFIED REMOVALS

Failed Unknown

Low Oil Pressure

Metal on Mag. Plug

TOTAL

1966

ENGINE RESPONSIBLE

1967

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---------------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Planet Gear and Bearing Assembly | - | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | - | 1 | 2 | - | 4 | - | 2 | 3 | 1 | 3 | - | 1 |
| Front Pinion | 2 | 1 | 1 | 1 | 1 | - | - | 2 | - | 1 | - | 1 | - | - | - | - | - | - | - | 2 | 1 | 1 | - | - |
| Rear Pinion | - | 1 | 1 | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 2 | 1 | 1 | - | - |
| Starter Shaft | - | 2 | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 | 1 | - | - | - |
| Hydraulic Pump Idler Gear | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Oil Pump Drive Idler | - | - | - | - | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | 1 | 3 | - | - | 1 |
| Main Idler Gear | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Main Drive Gear | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Prop Brake | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Prop Shaft Bearing | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| NIS Plunger | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Main Drive | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Alternator Drive | 1 | - | 1 | - | - | - | 1 | 2 | 1 | 1 | 1 | 3 | 1 | 1 | - | 1 | 1 | - | - | - | 1 | 1 | - | - |
| Hydraulic Pump Idler Drive | - | 2 | - | - | 1 | - | - | 1 | 1 | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Hydraulic Pump Idler | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Hydraulic Pump Drive | - | - | - | - | - | 1 | 1 | 1 | 1 | 1 | 1 | 2 | - | - | - | - | - | - | 1 | 1 | - | 1 | - | - |
| Starter | - | 2 | 1 | 1 | - | - | 1 | 1 | 1 | 1 | 2 | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - |
| Main Idler | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| SHAFT ASSEMBLY - HYDRAULIC PUMP DRIVE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| WASHER - OIL PUMP DRIVE GEAR | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| CAGE - OIL PUMP IDLER GEAR BEARING | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PRIMARY FAILURE UNDETERMINED | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| SHAFT - STARTER | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| SHAFT ASSEMBLY - ALTERNATOR DRIVE | 2 | 2 | 3 | 3 | 1 | 3 | 1 | 3 | 5 | 7 | 2 | 4 | 5 | 4 | 7 | 1 | 1 | 3 | 4 | 2 | 1 | 3 | 2 | 1 |
| DIAPHRAGM - R/G MAIN | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| CASE ASSEMBLY - R/G STUDDING - REAR | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| FLANGE - CARRIER OIL DELIVERY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PROPELLER BEARING ASSEMBLY | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PUMP - SCAVENGE OIL MAIN | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| JOURNAL - OIL PUMP DRIVE IDLER | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| BOLT - RING GEAR | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| NUT - PROP SHAFT THRUST BRG. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| FLANGE - STARTER DRIVE BRG. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| SPACER - UPPER HOULT | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| COUPLING - HELICAL SPLINE | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| CASE ASSEMBLY - R/G FRONT | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| BUSHING - SHAFT GEAR SPUR PINION | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| LOCK - TAB - RING GEAR | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| RING - MAIN DRIVE DAMPENER | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PUMP ASSY. - MAIN OIL | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| CAGE - NOSE BEARING | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| UNCLASSIFIED REMOVALS | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Failed Unknown | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Low Oil Pressure | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Metal on Mag. Plug | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| TOTAL | 7 | 15 | 12 | 12 | 5 | 12 | 10 | 7 | 15 | 14 | 9 | 18 | 18 | 11 | 13 | 8 | 21 | 14 | 11 | 15 | 14 | 13 | 6 | 13 |

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Table 3.2.1-V. Reduction Gear Premature Removals

REASON FOR REMOVAL - CLASSIFIED

SLEEVE - INNER SHAFT CENTER

COUPLING ASSEMBLY - SAFETY

DUCT ASSEMBLY - ANTI-ICING

"O" RING - T/M HOUSING REAR

FAILED UNKNOWN

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UNCLASSIFIED REMOVALS

Failed Unknown
Vibration

ENGINE RESPONSIBLE

| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2 | 1 | 3 | 5 | 1 | 1 | 1 | - | - | 1 | 1 | - | 2 |
| - | - | - | 1 | - | - | - | - | - | 2 | - | - | - |
| - | 1 | - | - | - | 1 | 1 | 1 | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | - |
| - | - | - | - | - | - | - | - | - | - | - | - | - |
| TOTAL | 2 | 2 | 3 | 6 | 1 | 2 | 1 | 0 | 3 | 1 | 1 | 3 |

FORM NO 2667 UNIT EXCHANGE 501-D13 AND 606 JANUARY 1968

Table 3.2.1-VI. Torquemeter Premature Removals

| REASON FOR REMOVAL | 1966 | | | | | | | | | | | | NON-ENGINE RESPONSIBLE | | | | | | | | | | | |
|----------------------------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
| IMPROPER PROCEDURE - MAINTENANCE | 1 | 1 | 2 | 1 | 2 | - | 2 | - | 1 | 1 | - | 5 | 6 | 3 | 6 | 9 | 8 | 8 | 3 | - | 2 | 1 | 1 | - |
| FOREIGN OBJECT DAMAGE | 1 | 2 | 1 | - | - | - | 1 | - | 2 | 1 | 2 | 1 | 2 | 2 | 2 | 2 | - | 1 | - | 1 | 1 | 2 | 2 | 2 |
| MODIFICATION | 2 | 1 | 1 | 1 | - | - | - | - | 2 | 3 | 1 | - | - | - | - | - | 2 | 1 | - | 2 | - | 1 | - | 4 |
| CONVENIENCE | 7 | 5 | 2 | 5 | 10 | 6 | 2 | 1 | 13 | 4 | 7 | 3 | - | 4 | 6 | 5 | 3 | 6 | 8 | 4 | 10 | 9 | 6 | 6 |
| QEC | - | 1 | 1 | - | - | 1 | - | 2 | - | - | 1 | - | - | - | - | - | - | - | - | 1 | - | - | - | - |
| ACCIDENT | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - | - | - | - | - | 2 | - | - | - |
| OVERTEMPERATURE | - | - | - | - | - | - | - | 1 | - | 2 | - | - | - | - | - | 2 | - | - | - | 4 | 1 | - | 1 | - |
| COMPRESSOR EROSION | 2 | 1 | 1 | - | 3 | 3 | 1 | 2 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| UNSUBSTANTIATED | 1 | 1 | 1 | 2 | - | 2 | 1 | 3 | - | 1 | 3 | 4 | 6 | 3 | 3 | 4 | - | 5 | 4 | 3 | 2 | 4 | 2 | - |
| TOTAL | 14 | 12 | 9 | 9 | 15 | 12 | 9 | 9 | 18 | 12 | 14 | 13 | 14 | 12 | 17 | 22 | 13 | 21 | 15 | 15 | 14 | 17 | 12 | 12 |

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Table 3.2.1-VII. Non-Engine Responsible Premature Removals

REGULATOR ASSEMBLY

1966

PROPELLER RESPONSIBLE

1967

REASON FOR REMOVAL - CLASSIFIED

SEALS:

Packing "O" Ring - Cover Bearing
Seal Assy. - Cover
Seal Assy. - Housing
Seal - Quad Ring (Pinion Screw)
Packing "O" Ring - Screw & Pinion
Packing "O" Ring - Feedback Drive
Packing "O" Ring - Feedback Brg.
Cord Seal

BEARINGS:

Cover

GEARS:

Condition

ELECTRICAL:

Slip Ring Assy.

PUMP ASSY. - REGULATOR

HOUSING - REGULATOR

FAILED UNKNOWN

RING - RETAINING

VALVE ASSEMBLY - BREATHER

SLEEVE ADAPTER - REGULATOR

PIN STOP - CONDITION GEAR

UNCLASSIFIED

Oil Leak
Failed Unknown
Binding
Metal on Mag. Plug

REGULATOR TOTAL

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| | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|-----------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Packing "O" Ring - Cover Bearing | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Seal Assy. - Cover | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Seal Assy. - Housing | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Seal - Quad Ring (Pinion Screw) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Packing "O" Ring - Screw & Pinion | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Packing "O" Ring - Feedback Drive | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Packing "O" Ring - Feedback Brg. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Cord Seal | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| BEARINGS: | | | | | | | | | | | | | | | | | | | | | | | | |
| Cover | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| GEARS: | | | | | | | | | | | | | | | | | | | | | | | | |
| Condition | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| ELECTRICAL: | | | | | | | | | | | | | | | | | | | | | | | | |
| Slip Ring Assy. | 1 | - | 1 | - | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | 1 | - | - | - | - | - |
| PUMP ASSY. - REGULATOR | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| HOUSING - REGULATOR | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| FAILED UNKNOWN | 1 | - | 1 | - | - | - | - | - | - | - | - | - | 2 | 1 | 1 | 1 | 3 | - | 3 | 3 | - | - | - | - |
| RING - RETAINING | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| VALVE ASSEMBLY - BREATHER | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| SLEEVE ADAPTER - REGULATOR | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| PIN STOP - CONDITION GEAR | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| UNCLASSIFIED | | | | | | | | | | | | | | | | | | | | | | | | |
| Oil Leak | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Failed Unknown | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Binding | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Metal on Mag. Plug | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| REGULATOR TOTAL | 8 | 4 | 5 | 6 | 2 | 6 | 4 | 6 | 14 | 9 | 9 | 6 | 13 | 6 | 12 | 8 | 7 | 5 | 12 | 10 | 1 | 9 | 8 | 3 |

Table 3.2.1-VIII. Propeller Regulator Premature Removals

1966

1967

NON-PROPELLER RESPONSIBLE

REASON FOR REMOVAL

| | 5 | 3 | - | 3 | - | 1 | 5 | - | 2 | 3 | 5 | - | 3 | 6 | - | 3 | 1 | 5 | 2 | 3 | 4 | 2 | 3 | 4 |
|--|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| IMPROPER PROCEDURE - A/L MAINTENANCE | 7 | 12 | 11 | 13 | 12 | 11 | 5 | 6 | 9 | 11 | 14 | 23 | 11 | 7 | 17 | 7 | 17 | 19 | 13 | 14 | 14 | 13 | 13 | 8 |
| CONVENIENCE | 1 | 1 | 2 | 1 | - | - | - | 1 | 1 | 2 | - | - | 1 | - | 1 | - | 1 | - | - | 1 | - | - | - | - |
| FOREIGN OBJECT DAMAGE | - | - | - | - | - | 1 | 1 | - | 2 | 1 | - | - | - | 1 | 1 | 1 | - | - | - | - | - | - | - | - |
| CONTAMINATION | 1 | 1 | 5 | 1 | 1 | 5 | 1 | 5 | 2 | 3 | 6 | 7 | 4 | 5 | 6 | 7 | 3 | 6 | 7 | 4 | 5 | 3 | 5 | 3 |
| UNSUBSTANTIATED | 10 | 3 | 2 | 3 | 1 | 1 | - | - | 2 | 1 | - | - | - | - | - | - | 13 | 7 | 16 | 12 | 8 | 21 | - | - |
| MODIFICATION | 2 | 2 | - | - | - | - | 2 | - | 3 | 1 | 1 | 2 | 3 | - | 1 | 2 | - | - | 2 | - | 6 | 1 | 1 | - |
| ACCIDENT | 26 | 22 | 20 | 23 | 14 | 19 | 14 | 12 | 21 | 22 | 26 | 32 | 27 | 19 | 32 | 22 | 35 | 37 | 40 | 34 | 35 | 40 | 22 | 15 |
| TOTAL NON-PROPELLER RESPONSIBLE REMOVALS | | | | | | | | | | | | | | | | | | | | | | | | |
| TIME EXPIRATION - HUB AND BLADE | 12 | 8 | 4 | 4 | 4 | 6 | 2 | 5 | 7 | 11 | 3 | 3 | 3 | 1 | 4 | 4 | 4 | 4 | 6 | 6 | 6 | 4 | 4 | 2 |
| TIME EXPIRATION - REGULATOR | 6 | 9 | 9 | 3 | 6 | 1 | 6 | 3 | 7 | 3 | 10 | 5 | 10 | 7 | 7 | 7 | 2 | 8 | 13 | 8 | 11 | 7 | 5 | 5 |
| TIME EXPIRATION - BLADE ONLY | 2 | - | 1 | 1 | 1 | - | 2 | 2 | 1 | - | - | - | 2 | - | 1 | 1 | 1 | 1 | - | - | - | - | - | 1 |
| TOTAL PROPELLER REMOVALS | 68 | 51 | 53 | 46 | 36 | 47 | 34 | 38 | 72 | 61 | 68 | 72 | 60 | 54 | 71 | 55 | 48 | 69 | 83 | 85 | 73 | 79 | 67 | 44 |
| FORM NO 2467 | | | | | | | | | | | | | | | | | | | | | | | | |
| UNIT EXCHANGE 501-D13 AND 606 | | | | | | | | | | | | | | | | | | | | | | | | |
| JANUARY 1968 | | | | | | | | | | | | | | | | | | | | | | | | |

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TOTAL PROPELLER REMOVALS

24

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Table 3.2.1-X. Non-Propeller Responsible Premature Removals and Time Expiration Removals

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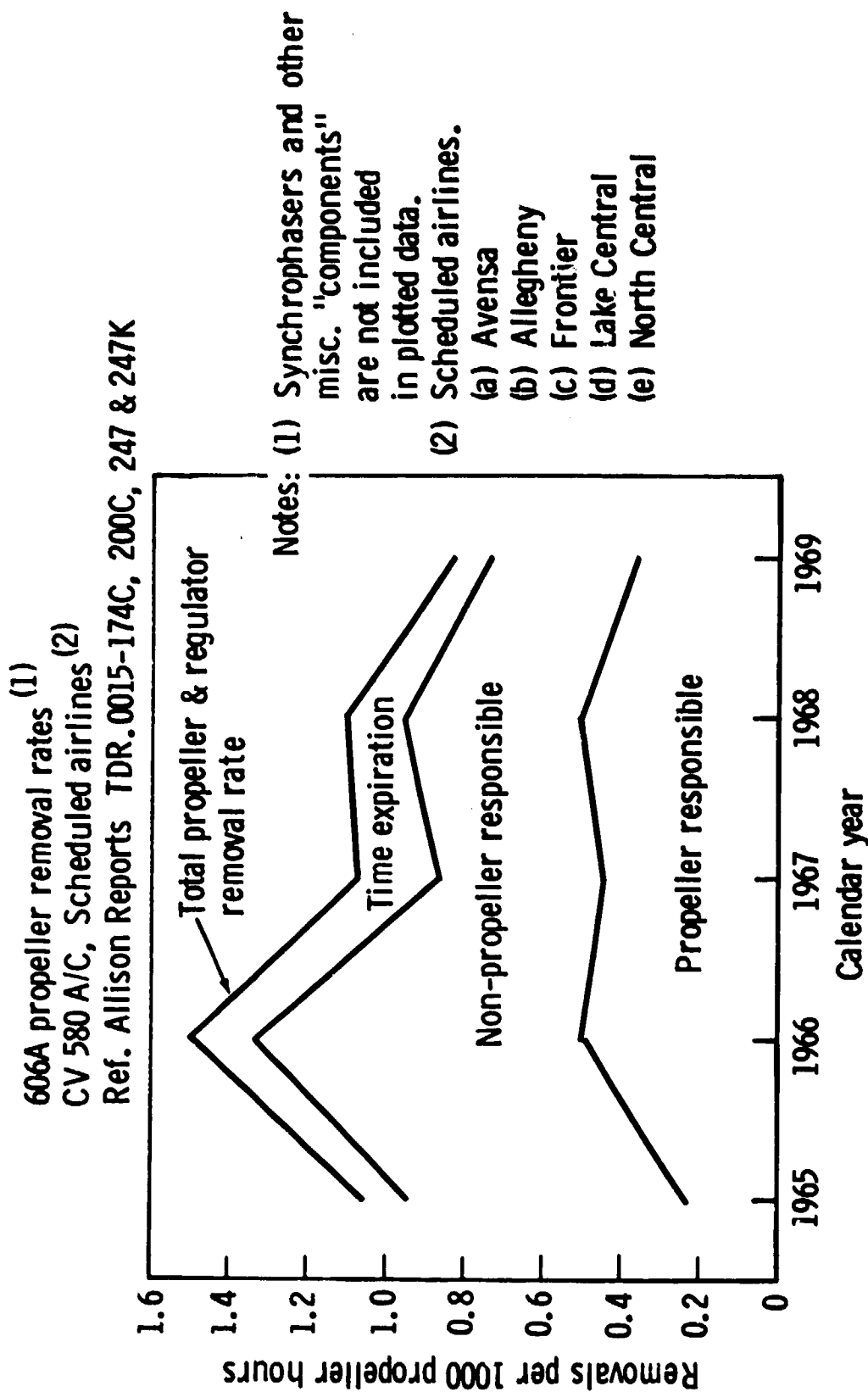


Figure 3.2.1.1-1. 606A propeller removal rates, CV580 aircraft, scheduled airlines.

606 Propeller removal rates (1)

Electra A/C, domestic & unit exch. airlines (2)

Ref. Allison Reports #TDR AR.0015-111E, 124K, 152K, 198K & 250

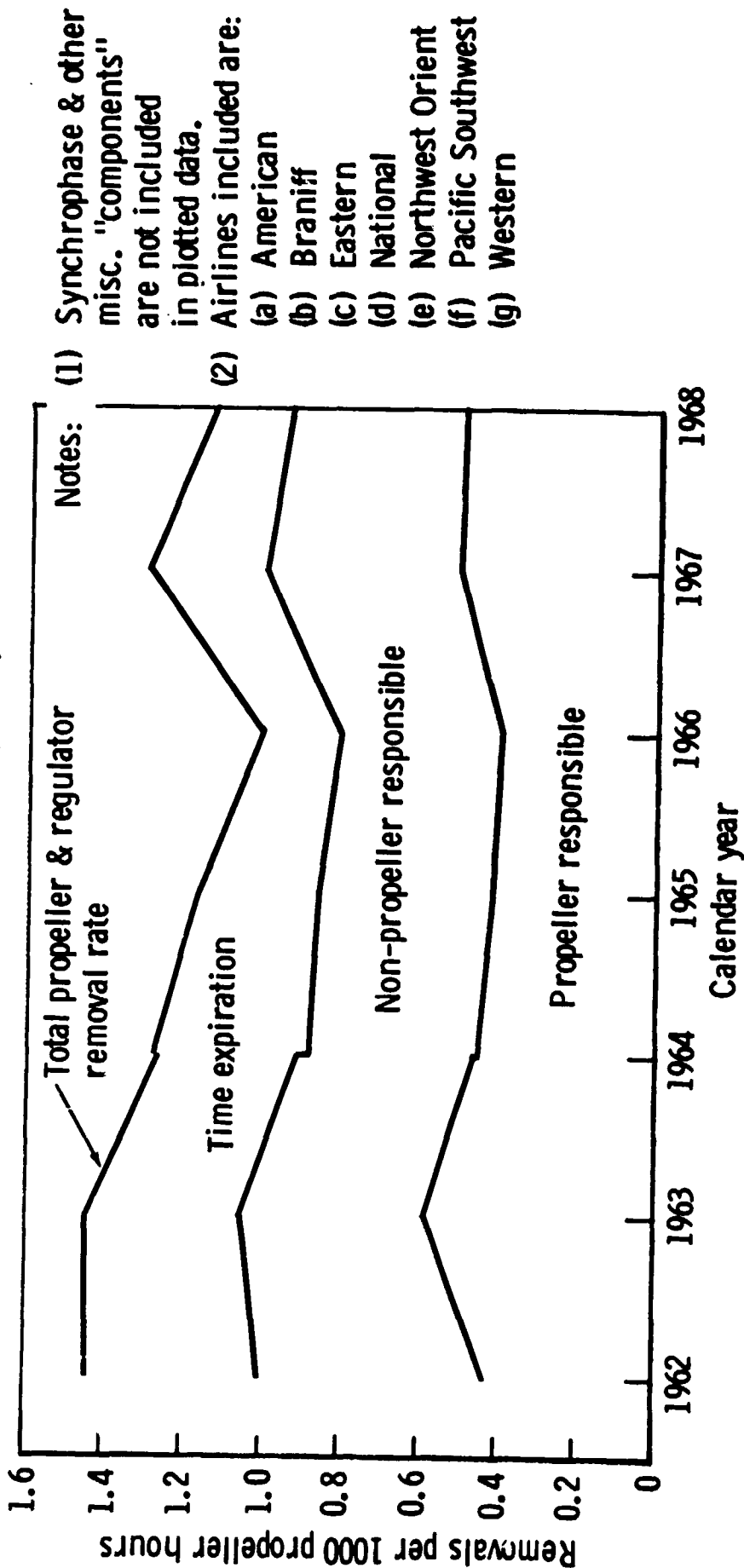


Figure 3.2.1.1-2. 606 propeller removal rates, Electra aircraft.

Table 3.2.1.2-1. Summary of Aeroproducts 606
Propeller Maintenance Cost Data

| <u>Airline</u> | <u>Aircraft</u> | <u>Data Period</u> | <u>Then Year \$ Per Hr.</u> | | |
|----------------|-----------------|------------------------|-----------------------------|--------------|--------------|
| | | | <u>Parts</u> | <u>Labor</u> | <u>Total</u> |
| Allegheny | CV580 | 1/66 - 9/66 | \$5.40 | \$1.01 | \$6.41 |
| American | Electra | 1965 | 2.09 | 2.02 | 4.11 |
| | Electra | 1/66 - 9/66 | 2.20 | 1.90 | 4.10 |
| Braniff | Electra | 1965 | 2.06 | 1.92 | 3.98 |
| | Electra | 1/66 - 9/66 | 2.06 | 1.74 | 3.80 |
| Eastern | Electra | 1965 | 4.51 | 0.37 | 4.88 |
| | Electra | 1/66 - 9/66 | 1.99 | 0.33 | 2.32 |
| Frontier | CV580 | 1965 | 4.52 | 1.07 | 5.59 |
| | CV580 | 1/66 - 9/66 | 1.21 | 1.40 | 2.61 |
| National | Electra | 1965 | 2.68 | 2.28 | 4.96 |
| | Electra | 1/66 - 9/66 | 2.88 | 2.39 | 5.27 |
| Pac. S. West | Electra | 1965 | 3.43 | 1.51 | 4.94 |
| Western | Electra | 1965 | 3.30 | 1.00 | 4.30 |
| | Electra | 1/66 - 9/66 | 1.86 | 0.70 | 2.56 |

3.2.2 CAB Form 41 Data

Direct engine maintenance costs and corresponding engine flight hours were available from published CAB data taken from reported airline costs on CAB Form 41. This data was available for Electra and CV580 operation by Carrier Group as well as by Individual Carrier. The means were available to break this data down to the components of labor, material and outside services.

The data reported by the CAB as direct engine maintenance included only the engine, gearbox, and QEC*, or any item of expense associated with ATA Chapters 71 through 80. The propeller (ATA Chapter 61) is reported in the CAB system under "Airframe and Other" direct maintenance cost. Therefore propeller direct maintenance costs were not available from published CAB data. Since the propeller is a major element of the turboprop propulsion system, it is recommended that the CAB consider inclusion of propeller maintenance costs as a part of engine or propulsion system maintenance costs for future turboprop aircraft.

The published CAB data that was readily convertible into engine maintenance cost per flight hour was available for the years CY 1965 through 1975.

*QEC - Quick Engine Change (included engine and gearbox and a major portion of the nacelle, as shown in Figure 3.2.2-1.)

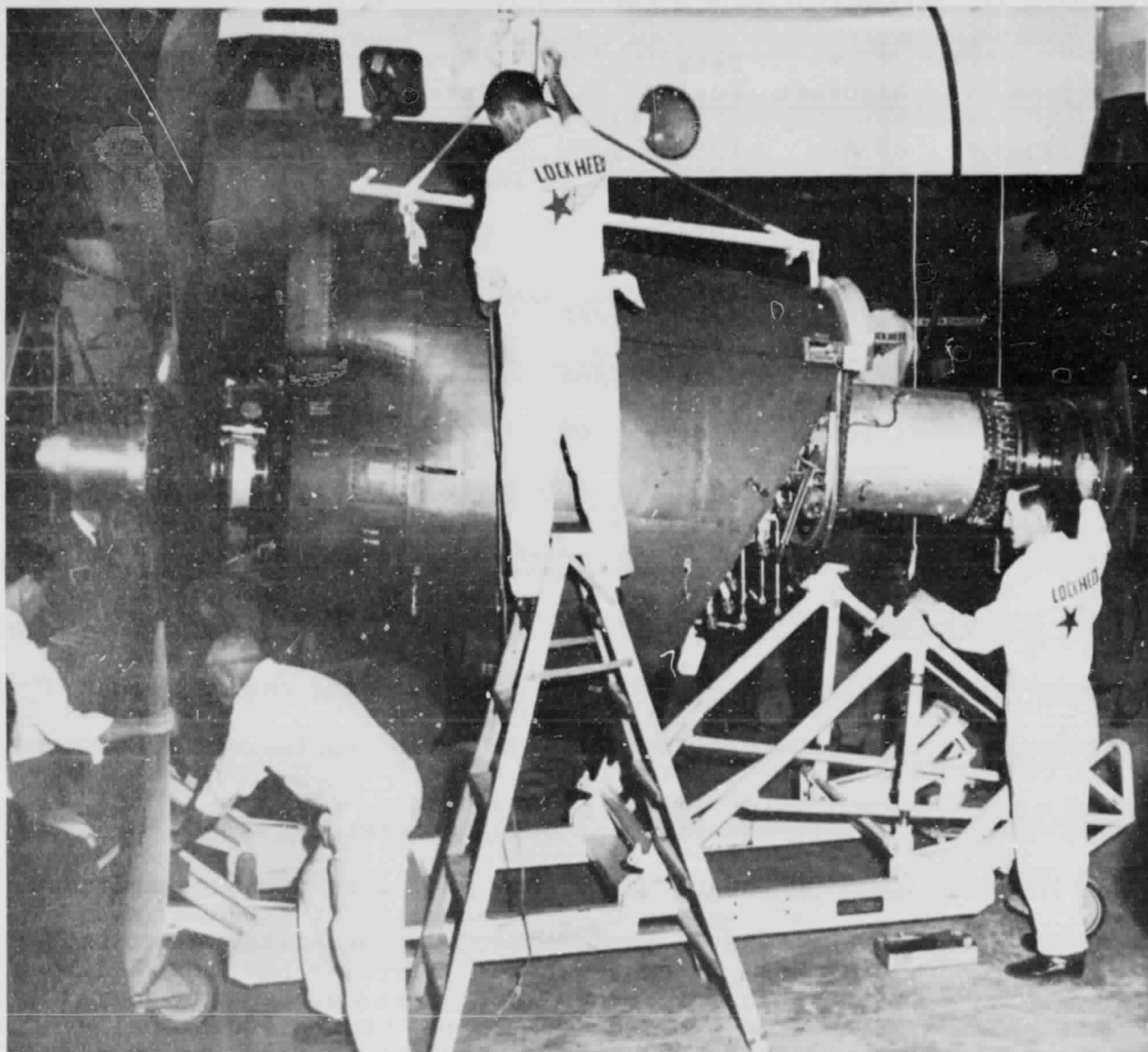


Figure 3.2.2-1. QEC removal from P3V

3.2.3 Airline Data

The reviews of the DDA in-house data and the CAB Form 41 data showed that neither was a source for detailed overhaul and repair costs that would enable the establishment of the maintenance cost drivers in the 501-D13/606 turboprop system. Detailed information of this type could only be obtained from operating airlines, or overhaul and repair facilities that were currently in the business of performing this work. Therefore arrangements were made to visit three airlines who were still operating either Electra, CV580, or L382 aircraft for purposes of collecting overhaul and repair costs, as well as removal rates and the reasons therefor. These sources were imperative for propeller cost and removal information since propeller cost information was not available in CAB Form 41 information to determine the overall cost per flight hour for the 606 and 54H60 propellers.

The three airlines that were visited for purposes of data collection were Eastern, Frontier, and Saturn; the latter is now merged with Trans International Airlines.

3.2.3.1 Frontier Airlines

Frontier Airlines uses the Convair CV580 airplane with the 501-D13 engine and 606 propeller. Frontier introduced the CV580 to scheduled airline service in CY 1964 and they are currently the heaviest user of the CV580 in terms of flight hours per year. Frontier's fleet size of CV580's reached a maximum of 32. In CY 1976 it was 28.

3.2.3.1.1 Engines and Reduction Gearboxes

At Frontier it was found that repair and overhaul of engines and gearboxes were a variable mix between their own shop and outside agencies. Detailed repair or overhaul of engine modules (compressor and turbine) usually is sent to an outside shop. A gearbox could be repaired or overhauled in the Frontier shop which is where repairs to the accessory drive section of the gearbox would usually be done, but dependent upon circumstances at the time a gearbox could also be sent to an outside agency. Frontier had also instituted a procedure for an interim inspection every 3800 hours of the accessory drive section of the gearbox while on the wing. Removal and repair of the accessory drive section would also be done with the remainder of the gearbox and propeller on the wing. The accessory drive section would be repaired in Frontier's shop.

Within the Frontier shop were smaller shops such as hydraulic, electric, welding, and machine which did work for the complete aircraft. Within these generalized shops the overall volume of engine costs could be segregated, but to break it down further to relate the repair or overhaul to specific removals required detailed work in their accounting system that was beyond the scope of effort that we could conduct with the airlines. It is the overall volume of engine and propeller costs which eventually find their way into the CAB Form 41 accounts, from which are determined the cost per flight hour or cost per block hour as published by the CAB.

A reliable source of engine and gearbox overhaul and repair costs which could be related to reasons for removal was found in the outside service costs. In these cases, where serialized engines or gearboxes were sent to outside services for overhaul or repair (related to a specific reason for premature removal), detailed charges for labor, material, and their outside services for either the overhaul or repair, as well as the primary failed item in the case of a premature removal were available. Samplings of the CY 1975 and CY 1976 outside service costs were taken for our detailed cost analysis.

Line maintenance costs were provided for engines and propellers but were not sufficiently detailed to split engine from propeller.

We were also provided with Frontier's Reliability and Statistical Analysis Reports covering a 16 month period of operation in CY 1975 and 1976, and a copy of their Maintenance Standards Manual which detailed standard manhours to perform maintenance functions. Together this information provided fleet size, daily utilization, numbers of various maintenance checks, premature and scheduled removals by ATA chapter, delays, cancellations, maintenance standard manhours, and number of spare engines and propellers.

3.2.3.1.2 Propellers

The available information with regard to Aeroproducts 606 propeller data, based on Frontier CV580 fleet operation can be summarized as follows:

- Records of removals, including causes, were available via Propeller Condition Reports.
- Overhaul and repair of major propeller assemblies is performed by Frontier Airlines with the exception of major blade and barrel rework which is contracted.
- The maintenance facility is organized by shops such as the electrical shop and the hydraulic shop. Costs are controlled by these shops such that the costs of repairing or overhauling propeller hardware cannot be isolated.
- Outside services charges for blade overhaul and repair were available.
- Line maintenance cost records are available but are not sufficiently detailed to permit identification of the portion chargeable to propellers.

Frontier Airlines Propeller Condition Reports for the period January 1976 thru July 1976 were analyzed to compile statistical data regarding causes of removals of Hub and Blade Assemblies, Blades, and Regulators. The results are summarized in Table 3.2.3.1.2-I.

In addition to the data for major propeller assemblies received from Frontier Airlines, information was received from DDA regarding Frontier component removals during 1975. This data is summarized in Table 3.2.3.1.2-II.

3.2.3.2 Saturn Airways (Trans International Airlines)

The Saturn Airways fleet consisted of nine Electras and twelve Commercial Hercules (L-382's). The significance of visiting Saturn was that they currently operate the largest fleet of commercial turboprop aircraft that are equipped with Hamilton Standard propellers.

3.2.3.2.1 Engines and Reduction Gearboxes

At Saturn it was found that over 90% of their engine repair and overhaul was done by outside agencies. Essentially only line maintenance was done by Saturn, and from data furnished by Saturn, line maintenance for engines and propellers during the first nine months of CY 1976 was between 15.8 and 26.9 percent of the total

TABLE 3.2.3.1.2-I

SUMMARY OF FRONTIER AIRLINES 606 PROPELLER ASSEMBLY REMOVALS
 BASED ON PROPELLER CONDITION REPORTS
 PERIOD 1/76 THRU 7/76
 (74,702 PROPELLER FLIGHT HOURS)

| <u>Reason for Removal</u> | <u>Number of Removals</u> | <u>Removal Rate, Removals per 1000 Propeller Flight Hrs.</u> |
|----------------------------------|-------------------------------|--|
| <u>HUB & BLADES ASSEMBLY</u> | | |
| Overhaul | 7 | .094 |
| Interim Inspection | 14 | .187 |
| Hub Airworthiness Directive | 1 | .013 |
| Unjustified | 1 | .013 |
| Impact Damage | 3 | .040 |
| Leaking | 4 | .054 |
| Miscellaneous | 1 | .013 |
| <u>BLADES</u> | | |
| Blade Airworthiness Directive | 2 | .027 |
| Burned Cuffs | 9 | .120 |
| Blade Heater Lead Broken | 4 | .054 |
| Blade Cuff Separated | 3 | .040 |
| Miscellaneous | 2 | .027 |
| <u>REGULATOR</u> | | |
| Overhaul | 10 | .134 |
| Unjustified | 3 | .040 |
| Leaking | 9 | .120 |
| Metal on Magnetic Plug | 2 | .027 |
| Slip Ring Assembly | 2 | .027 |
| Miscellaneous | <u>7</u> | <u>.094</u> |
| TOTAL | 84 | 1.124 |

TABLE 3.2.3.1.2-II

FRONTIER AIRLINES COMPONENT REMOVALS
DURING 1975 (606 PROPELLER)
(128,326 PROPELLER FLIGHT HOURS)

| <u>Component</u> | <u>Number of Removals</u> | <u>Removal Rate Removals per 1000 Propeller Flight Hrs.</u> |
|-------------------------|-------------------------------|---|
| Alternator | 25 | .195 |
| Prop Sync Assy | 124 | .966 |
| Solenoid Valve | 101 | .787 |
| Feather Solenoid | 4 | .031 |
| Thrust Sens. Switch | 9 | .070 |
| Solenoid Stop | 15 | .117 |
| Feather Relay | 8 | .062 |
| Feather Pump Meter | 3 | .023 |
| Reservoir | 65 | .507 |
| Rotary Actuator | 78 | .608 |
| Governor Valve | 96 | .748 |
| Pitch Lock & Stop Valve | 63 | .491 |
| NTS Valve | 68 | .530 |
| Spinner | 11 | .086 |
| TOTAL | 670 | 5.221 |

direct maintenance for engines and propellers, where the 26.9% also included some periodic inspections and some modifications. From this data it was concluded that at Saturn, line maintenance of engines and propellers together were on the order of 20 percent or less of total direct maintenance. With the information that was available there was no way of splitting the engine and propeller line maintenance costs into their respective values.

Engine and gearbox removal statistics were provided to us for the period CY 1974 through September of CY 1976. This included the reason for each removal. The majority of engine and gearbox overhaul and repair was performed by outside agencies and cost documentation of this effort was very complete, including the findings for failure in the case of a premature removal. This information allowed an assessment to be made of repair costs for specific failure reasons, which was necessary in the determination of maintenance cost drivers.

Since overhaul and repair were performed by outside agencies, averages for these operations are summarized in Section 3.2.4.

3.2.3.2.2 Hamilton Standard 54H60 Propeller

Following is a summary of the significant information obtained with regard to Hamilton Standard propellers:

- All propeller repair and overhaul work is contracted to outside repair facilities. A work order is prepared for each item of removed equipment and an invoice is received from the repair facility when the work is completed. Thus, accurate CY 1975 shop cost records were available.
- Line maintenance cost records are not sufficiently detailed to permit identification of charges which relate to propellers.
- Records were available indicating the reason for removal of major propeller assemblies.
- Detailed analyses of failed hardware to establish the cause of failure were not available.

Outside services from the year 1975 were analyzed to establish average overhaul and repair costs for the various propeller assem-

blies. Frequencies of occurrence were established based on the number of Work Orders issued during 1975 and the Premature Removals Summary Report compiled by the Saturn Reliability Dept. Removal rates and maintenance costs by component are summarized in Tables 3.2.3.2.2-I and 3.2.3.2.2-II for the L188 and L382 aircraft respectively.

3.2.3.3 Eastern Airlines

Eastern Airlines in CY 1976 still had a standby fleet of 14 Electras for shuttle use in the East Coast corridor. Eastern has been doing their own overhaul and repair of 501-D13 engines and they operate the Aeroproducts 606 propeller which they also overhaul and repair. In addition to their own requirements, Eastern also performed overhaul and repair of the engine, gearbox, and propeller for other Electra operators who operate in the Caribbean and South America. Eastern now has their fleet of Electras for sale and they are selling their engine and propeller overhaul and repair equipment to other repair agencies.

3.2.3.3.1 Engine and Reduction Gearboxes

Eastern Airlines were able to provide overhaul and repair cost data back to CY 1967. Table 3.2.3.3.1-I is a summarization of this data. In this table the module overhaul and engine repair costs are an average for each unit processed in the shop. These costs were for the shop effort only and did not include line maintenance such as line labor and any material charges that did not result in shop overhaul and repair costs.

At Eastern the relationship of the cost of line to shop maintenance was studied from a tabulation of cost data for CY 1974 and 1975. This data showed that line maintenance costs for these two years were 18.3 and 20.9 percent of the total maintenance costs of the engine and gearbox.

3.2.3.3.2 Propeller

The significant information obtained during this trip with regard to 606 propeller data based on Eastern Airlines Electra fleet operation is as follows:

TABLE 3.2.3.2.2-i

**SUMMARY OF SATURN AIRLINES REMOVAL RATES AND AVERAGE
OVERHAUL AND REPAIR COSTS FOR ELECTRA (L-188) PROPELLER
1975 ECONOMY
(88,858 PROPELLER FLIGHT HOURS)**

| <u>Component/Item</u> | <u>Removal Rate Removals per 1000 Hrs</u> | <u>Labor Charge, \$</u> | <u>Material Charge, \$</u> | <u>Total Charge, \$/Event</u> |
|---------------------------------|---|-----------------------------|--------------------------------|---------------------------------------|
| Propeller Assembly | | | | |
| Overhaul | .135 | \$2,969 | \$7,271 | \$10,240 |
| Repair | .169 | 1,551 | 1,110 | 2,661 |
| Control Unit | | | | |
| Overhaul | .180 | 1,000 | 1,720 | 2,720 |
| Repair | .146 | 670 | 46 | 716 |
| Valve Housing | | | | |
| Overhaul | .202 | 832 | 1,316 | 2,148 |
| Repair | .315 | 403 | 399 | 802 |
| Pitchlock Regulator | .225 | 162 | 318 | 480 |
| Synchrophaser(1) | .428 | 249 | 48 | 297 |
| Miscellaneous Components | .191 | 152 | 201 | 353 |

- (1) The Synchrophaser is common to both the L-188 and L-382 aircraft. Costs are based on the average for all synchrophasers repaired during 1975. Removal Rate is based on the number of removals from the L-188 aircraft fleet only during 1975.

TABLE 3.2.3.2.2-II

**SUMMARY OF SATURN AIRLINES REMOVAL RATES AND AVERAGE
OVERHAUL AND REPAIR COSTS FOR HERCULES (L-382) PROPELLER
1975 ECONOMY
(162,452 PROPELLER FLIGHT HOURS)**

| <u>Component/Item</u> | <u>Removal Rate Removals per 1000 Hrs</u> | <u>Labor Charge, \$</u> | <u>Material Charge, \$</u> | <u>Total Charge, \$/Event</u> |
|----------------------------|---|-----------------------------|--------------------------------|---------------------------------------|
| Propeller Assembly | | | | |
| Overhaul | .068 | \$4,339 | \$4,513 | \$8,852 |
| Repair | .160 | 1,384 | 1,813 | 3,197 |
| Control Unit | | | | |
| Overhaul | .111 | 890 | 2,131 | 3,021 |
| Repair | .111 | 646 | 1,004 | 1,650 |
| Valve Housing | | | | |
| Overhaul | .092 | 951 | 1,560 | 2,511 |
| Repair | .209 | 394 | 200 | 594 |
| Pitchlock Regulator | .068 | 172 | 350 | 522 |
| Synchrophaser (1) | .350 | 249 | 48 | 297 |

- (1) The Synchrophaser is common to both the L-188 and L-382 aircraft. Costs are based on the average for all synchrophaser^s repaired during 1975. Removal Rate is based on the number of removals from the L-382 aircraft fleet only during 1975.

Table 3.2.3.3.1-1

SUMMARY OF ACTUAL MAJOR MODULE AVERAGE SHOP MAINTENANCE COSTS
501-D13 ENGINE AND GEARBOX
EASTERN AIRLINES, INC.

| AVERAGE ENGINE OVERHAUL COST PER MODULE | CY | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 Thru Sept. |
|---|----|---------|---------|---------|--------|--------|--------|--------|--------|--------|-----------------------|
| COMPRESSOR | | | | | | | | | | | |
| LABOR HRS. | | 871 | 966 | 1,106 | 396 | 1,673 | 1,679 | 1,341 | 1,763 | 1,411 | 761 |
| LABOR \$ | | 3,571 | 4,202 | 5,419 | 2,210 | 9,630 | 11,026 | 9,333 | 12,888 | 11,286 | 6,270 |
| MATERIAL \$ | | 9,424 | 8,370 | 8,498 | 14,781 | 16,546 | 14,956 | 15,875 | 17,423 | 19,341 | 16,100 |
| OSS \$ | | 1,710 | 1,795 | 3,411 | 4,059 | 2,074 | 1,360 | 3,606 | 3,209 | 1,536 | 3,321 |
| TOTAL \$ | | 14,705 | 14,367 | 17,328 | 21,050 | 28,250 | 27,341 | 28,814 | 33,520 | 32,163 | 25,691 |
| TURBINE | | | | | | | | | | | |
| LABOR HRS. | | 198 | 243 | 317 | 385 | 398 | 358 | 539 | 655 | 709 | 712 |
| LABOR \$ | | 812 | 1,057 | 1,553 | 2,148 | 2,263 | 2,351 | 3,751 | 4,788 | 5,671 | 5,876 |
| MATERIAL \$ | | 11,685 | 11,400 | 10,116 | 10,577 | 11,771 | 11,820 | 12,469 | 23,686 | 18,079 | 22,437 |
| OSS \$ | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTAL \$ | | 12,497 | 12,457 | 11,669 | 12,725 | 14,034 | 14,171 | 16,220 | 28,474 | 23,750 | 28,313 |
| REDUCTION GEAR | | | | | | | | | | | |
| LABOR HRS. | | 321 | 334 | 434 | 444 | 554 | 415 | 558 | 745 | 945 | 639 |
| LABOR \$ | | 1,316 | 1,453 | 2,127 | 2,478 | 3,180 | 2,725 | 3,884 | 5,446 | 7,420 | 5,234 |
| MATERIAL \$ | | 2,470 | 2,660 | 2,534 | 4,935 | 4,797 | 4,327 | 4,092 | 9,779 | 17,122 | 4,315 |
| OSS \$ | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TOTAL \$ | | 3,786 | 4,113 | 4,661 | 7,413 | 7,977 | 7,052 | 7,976 | 15,225 | 24,542 | 9,549 |
| AVERAGE COST PER ENGINE REPAIR | | | | | | | | | | | |
| LABOR HRS. | | 544 | 552 | 677 | 815 | 964 | 641 | 471 | 592 | 587 | 954 |
| LABOR \$ | | 2,230 | 2,401 | 3,317 | 4,548 | 5,448 | 4,209 | 3,278 | 4,328 | 4,669 | 7,905 |
| MATERIAL \$ | | 2,850 | 2,774 | 4,537 | 6,291 | 8,640 | 6,326 | 4,308 | 5,122 | 5,574 | 4,647 |
| OSS \$ | | 380 | 257 | 822 | 857 | 1,061 | 1,248 | 2,205 | 609 | 1,046 | 1,188 |
| TOTAL | | 5,460 | 5,432 | 8,676 | 11,696 | 15,149 | 11,783 | 9,791 | 10,059 | 11,289 | 13,740 |
| ENGINE SHOP SUPPORT PER ENGINE FLIGHT HOUR | | | | | | | | | | | |
| LABOR \$ | | 1.35 | 1.12 | 2.03 | 2.19 | 2.76 | 2.54 | 2.04 | 2.37 | 1.85 | 0.98 |
| MATERIAL \$ | | 2.64 | 1.80 | 3.02 | 4.13 | 4.36 | 1.37 | 3.69 | 6.31 | 2.08 | 0.43 |
| OSS \$ | | 0.45 | 0.47 | 0.54 | 1.28 | 1.13 | 0.42 | 0.84 | 1.52 | 1.52 | 0.02 |
| TOTAL | | 4.44 | 3.39 | 5.59 | 7.60 | 8.25 | 4.33 | 6.57 | 10.20 | 5.85 | 1.43 |
| TOTAL ENGINE FLIGHT HOURS PER YEAR | | | | | | | | | | | |
| ENGINE FLIGHT HOURS | | 396,280 | 231,316 | 112,540 | 70,592 | 60,664 | 65,320 | 68,892 | 41,988 | 43,536 | 35,336 |
| TOTAL COST PER ENGINE FLIGHT HOUR* | | | | | | | | | | | |
| COST PER HOUR, \$ | | 12.71 | 13.03 | 14.84 | 23.53 | 35.54 | 28.89 | 32.25 | 36.61 | 28.66 | --- |

*DOES NOT INCLUDE LINE LABOR

- Line maintenance chargeable to propellers was obtained based on records from the years 1974 and 1975:
 - (a) Line labor is 20.8 percent of total propeller labor cost.
 - (b) Line material is 2.6 percent of total propeller material cost.
- Propeller shop maintenance costs were obtained from several periods of time. A summary of this data is as follows:

| <u>Data Period</u> | <u>Propeller Maintenance Cost, Then-Year Dollars per Propeller Flight Hour</u> |
|--------------------|--|
| 1/68 thru 12/69 | \$ 4.58 |
| 1974 | 14.44 |
| 1975 | 14.27 |
| 1/76 thru 11/76 | 7.85 |

- Removal rates for propeller assemblies were obtained for each of the above data periods. This data is summarized in Figure 3.2.3.3.2-1.
- Summaries of propeller failure mode data from the periods 1966, 1967, 1968, 1972 and 1973 were obtained from Eastern Airlines Fleet Reliability Reports. This data is presented in Table 3.2.3.3.2-I.
- Maintenance costs by failure mode or repair action were not available.

3.2.4 Repair Facilities

It was noted in Section 3.2.3 that of the airlines from whom cost data was obtained, Frontier and Saturn had a large percentage of their work done by outside repair facilities, while Eastern did their own work with the exception of a small percentage (4%) sent outside for specialized operations. Repair facility data was reviewed to obtain a representative sampling of overhaul and repair costs for engines, gearboxes, and propellers.

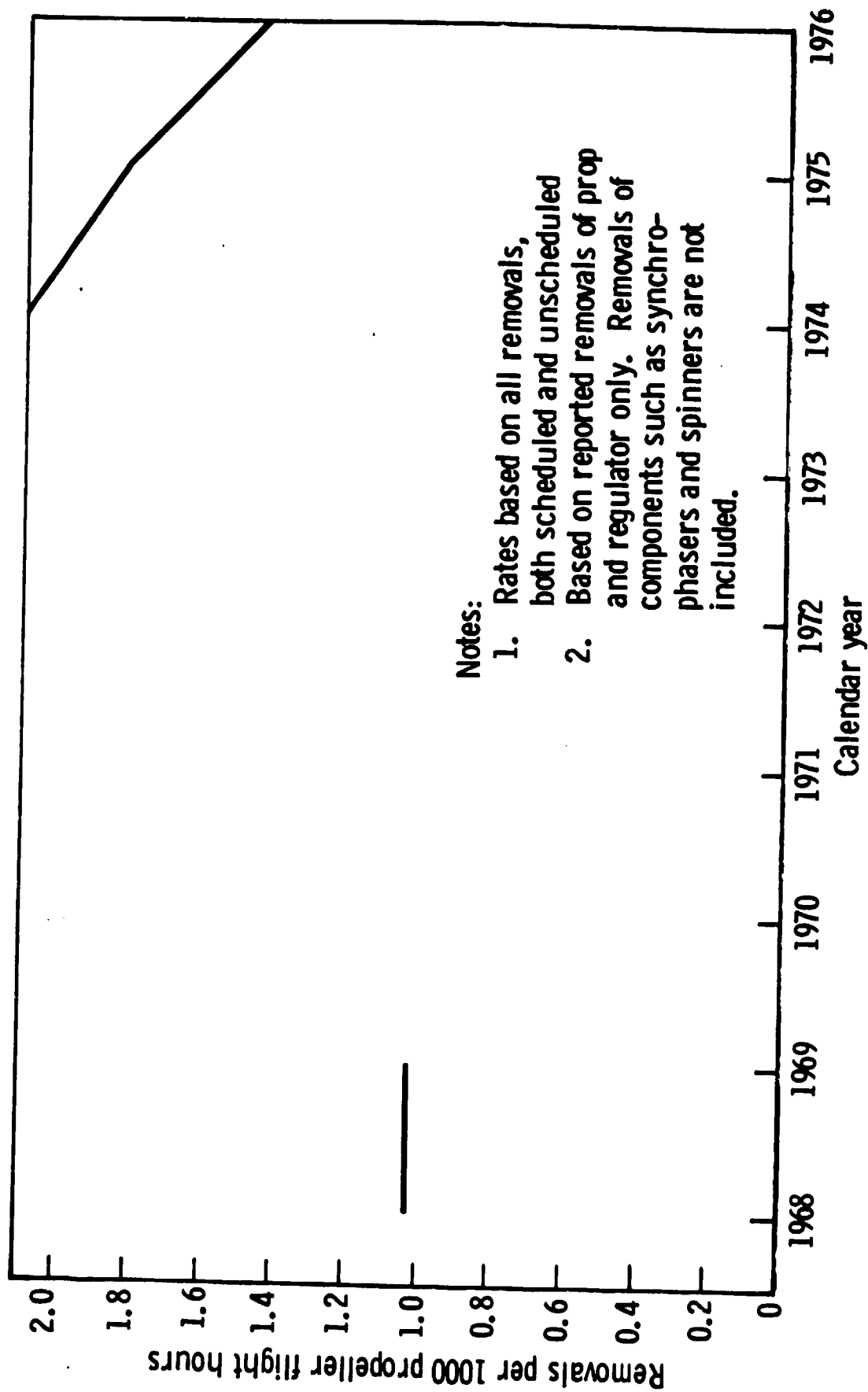


Figure 3.2.3.3.2-1. Summary Eastern Airlines Electra 606 propeller and regulator removal rate.

Table 3.2.3.3.2-1

SUMMARY OF EASTERN AIRLINES ELECTRA 606 PROPELLER FAILURE
MODE DATA

| | 1966 | 1967 | 1968 | 1972 | 1973 |
|---|---------|---------|---------|--------|--------|
| <u>Inherent Failure Modes</u> | | | | | |
| Oil Leaks | 55 | 42 | 64 | 2 | 2 |
| Vibration | 14 | 14 | 3 | 3 | 2 |
| De-Ice Elements | 47 | 61 | 44 | 2 | 0 |
| All Others | 30 | 22 | 21 | 8 | 8 |
| Investigation Incomplete | 0 | 0 | 2 | 0 | 2 |
| TOTAL INHERENT | 146 | 139 | 132 | 5 | 9 |
| <u>Inherent Failure Modes</u> | | | | | |
| Seal: Blade Shank; Grease: Cut | | | | 2 | 2 |
| Seal: Hub to Reg Transf Tube; Brittle | | | | 3 | 2 |
| Seals: Reg Adapter Bore; Worn | | | | 2 | 0 |
| Seals: Hub to Reservoir; Brittle Leaking | | | | 8 | 8 |
| Condition Lever Assy; Worn & Binding | | | | 0 | 2 |
| Seals: Hub Torque Cyl; Quad Config. Leaking | | | | 9 | 9 |
| Seal: Feather Reservoir Housing Leaking | | | | 5 | 9 |
| Gasket: Regulator Cover; Leaking | | | | 0 | 1 |
| Seal: Feedback Drive Gear; Leaking | | | | 0 | 1 |
| Hyd Gov: Speed Sense Element Arm Binding | | | | 0 | 1 |
| Pump, Worn Displacement Gears | | | | 0 | 2 |
| All Others | | | | 24 | 13 |
| Investigation Incomplete | | | | 0 | 1 |
| TOTAL INHERENT | | | | 53 | 51 |
| <u>Non-Inherent Failure Modes</u> | | | | | |
| Personnel & Procedures | 42 | 86 | 87 | 21 | 21 |
| Maintenance Convenience | 0 | 0 | 1 | 1 | 0 |
| Precautionary | 9 | 0 | 0 | 16 | 7 |
| Reliability Project | 0 | 77 | 0 | 29 | 44 |
| FOD | 7 | 3 | 5 | | |
| TOTAL NON-INHERENT | 58 | 166 | 93 | 67 | 72 |
| TOTAL FAILURES | 204 | 305 | 225 | 120 | 123 |
| Propeller Flight Hours | 359,876 | 399,848 | 231,584 | 65,248 | 68,892 |

3.2.4.1 Engines and Gearboxes

From a sampling of outside service costs at Frontier and Saturn, overhaul and repair costs for the major modules were determined. In the case of repairs (premature removals) the cause of the removal had also been recorded so that classification of the repair cost by reason could be made. This information was used as guidance in the determination of cost drivers. Table 3.2.4.1-I shows average overhaul and repair costs by major module as determined from outside service charges to Frontier and Saturn.

3.2.4.2 Propellers

Overhaul and repair records from various repair facilities for both Hamilton Standard 54H60 and Aerorproducts 606 propellers were reviewed. The following summary lists the type of information available:

- A work order exists for each assembly returned for overhaul or repair.
- The records indicate the action taken; i.e., overhaul or repair.
- Labor and material costs for overhaul and repairs are recorded.

A history regarding the circumstances or causes of unscheduled removals was not available. Consequently there was no record of the reason for removal and thus no basis for analyzing the hardware to determine the cause of failure.

CY 1976 records for the 606 propeller and CY 1975 records for the 54H60 propeller were available. This data was analyzed to establish average per event overhaul and repair costs for the various propeller assemblies. A summary of the cost data is presented in Table 3.2.4.2-I. As will be seen later in this report, data for the 606 propeller was used to develop per propeller flight hour maintenance costs using Frontier Airlines frequencies of events (Reference paragraph 3.2.3.1.2 and Table 3.2.3.1.2-I).

Table 3.2.4.1-1

Summary of Repair Facilities Charges
501-D13 Average Shop Costs Per Major Module
CY 1976 Economy

| <u>Module</u> | <u>Labor \$</u> | <u>Material \$</u> | <u>Total \$</u> |
|------------------------------|-----------------|--------------------|-----------------|
| Compressor | | | |
| Overhaul | 7,439 | 30,498 | 37,937 |
| Repair * | 3,455 | 10,496 | 13,951 |
| Turbine | | | |
| Overhaul | 4,268 | 29,115 | 33,383 |
| Repair * | 2,085 | 9,146 | 11,231 |
| Combustor | | | |
| Overhaul | 1,244 | 2,225 | 3,469 |
| Repair | N/A | N/A | N/A |
| Reduction Gear & Torquemeter | | | |
| Overhaul | 6,049 | 8,780 | 14,829 |
| Repair | 1,394 | 3,026 | 4,420 |
| Accessories | | | |
| Overhaul/Repair | 1,911 | N/A | 1,911 |

* Does not include major repair such as rear compressor bearing failure or blade failures which result in the equivalent of a complete overhaul.

TABLE 3.2.4.2-I
SUMMARY OF REPAIR FACILITIES DATA
AVERAGE SHOP COSTS, PER EVENT

AEROPRODUCTS 606 PROPELLER SHOP COSTS, 1976 ECONOMY

| <u>Component/Item</u> | <u>Labor Charge</u> | <u>Material Charge</u> | <u>Total</u> |
|---------------------------|---------------------|------------------------|--------------|
| Propeller Assembly | | | |
| Overhaul | \$6,287 | \$5,172 | \$11,459 |
| Interim Inspection | 1,700 | 800 | 2,500 |
| Repair | 2,949 | 2,663 | 5,612 |
| Regulator | | | |
| Overhaul | 3,518 | 4,852 | 8,370 |
| Repair | 1,288 | 1,268 | 2,556 |
| Blades | | | |
| Overhaul | 965 | 760 | 1,725 |
| Repair | 423 | 552 | 975 |

HAMILTON STANDARD 54H60 PROPELLER SHOP COSTS, 1975 ECONOMY

SATURN ELECTRA (L-189) PROPELLER

| <u>Component/Item</u> | <u>Labor Charge</u> | <u>Material Charge</u> | <u>Total</u> |
|--|---------------------|------------------------|--------------|
| Propeller Assembly | | | |
| Overhaul | \$3,209 | \$7,859 | \$11,068 |
| Repair | 2,026 | 1,451 | 3,477 |
| Pump Housing | | | |
| Overhaul | 811 | 1,975 | 2,786 |
| Repair | 439 | 177 | 616 |
| Valve Housing | | | |
| Overhaul | 889 | 1,955 | 2,844 |
| Repair | 422 | 726 | 1,148 |
| Miscellaneous Components, Repair* | 228 | 267 | 495 |

*Pitch lock Regulator, Spinner, Afterbody, Delcer Timer

Note the similarity of the repair facilities data on the 54H60 propeller with data acquired from Saturn and presented in Tables 3.2.3.2.2-I and II.

3.2 Baseline Turboprop Propulsion System Maintenance Cost

As a starting point it was necessary to establish the direct maintenance cost of the turboprop system consisting of the 501-D13 engine and gearbox and the 606 and 54H60 propeller. For proper comparisons with turbofan systems, it was necessary to make the comparison on the basis of a mature system. Since the calendar year(s) of maturity would not be the same, it was also necessary to express the data in constant year dollars. The 1976 economy was chosen as the basis for all comparisons.

Direct maintenance costs for the 501-D13 engine and gearbox were reported in published CAB Form 41 data. This data was used to form the engine and gearbox baseline maintenance cost. Since propeller costs were not specifically identified in published CAB data, a propeller cost had to be calculated that was based upon removal rates and overhaul and repair costs obtained from the airlines.

3.3.1 Engine, Reduction Gearbox, QEC

Published CAB Form 41 data for the Electra and CV580 aircraft operation from CY1965 to CY1975 was collected for analysis. From this data the total direct engine, gearbox, and QEC maintenance cost in dollars per engine flight hour was calculated for each year. The results are shown in Figure 3.3.1-1.

The Electra L-188's were operated by the Domestic Trunk Airlines and the Convair CV580's were operated by the Domestic Local Service Airlines, and are classified as such in the CAB data. This data was a summation of reported expenses by the airlines that are shown in Tables 3.3.1-I and 3.3.1-II.

Table 3.3.1-I

Electra L-188 Operators - Domestic Trunk Airlines

| CY | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 |
|----------------|------|------|------|------|------|------|------|------|------|------|------|
| <u>Airline</u> | | | | | | | | | | | |
| American | X | X | X | X | | | | | | | |
| Braniff | X | X | X | X | X | | | | | | |
| Eastern | X | X | X | X | X | X | X | X | X | X | |
| National | X | X | X | X | | | | | | | |
| Northwest | X | X | X | X | X | X | | | | | |
| Western | X | X | X | X | | | | | | | |

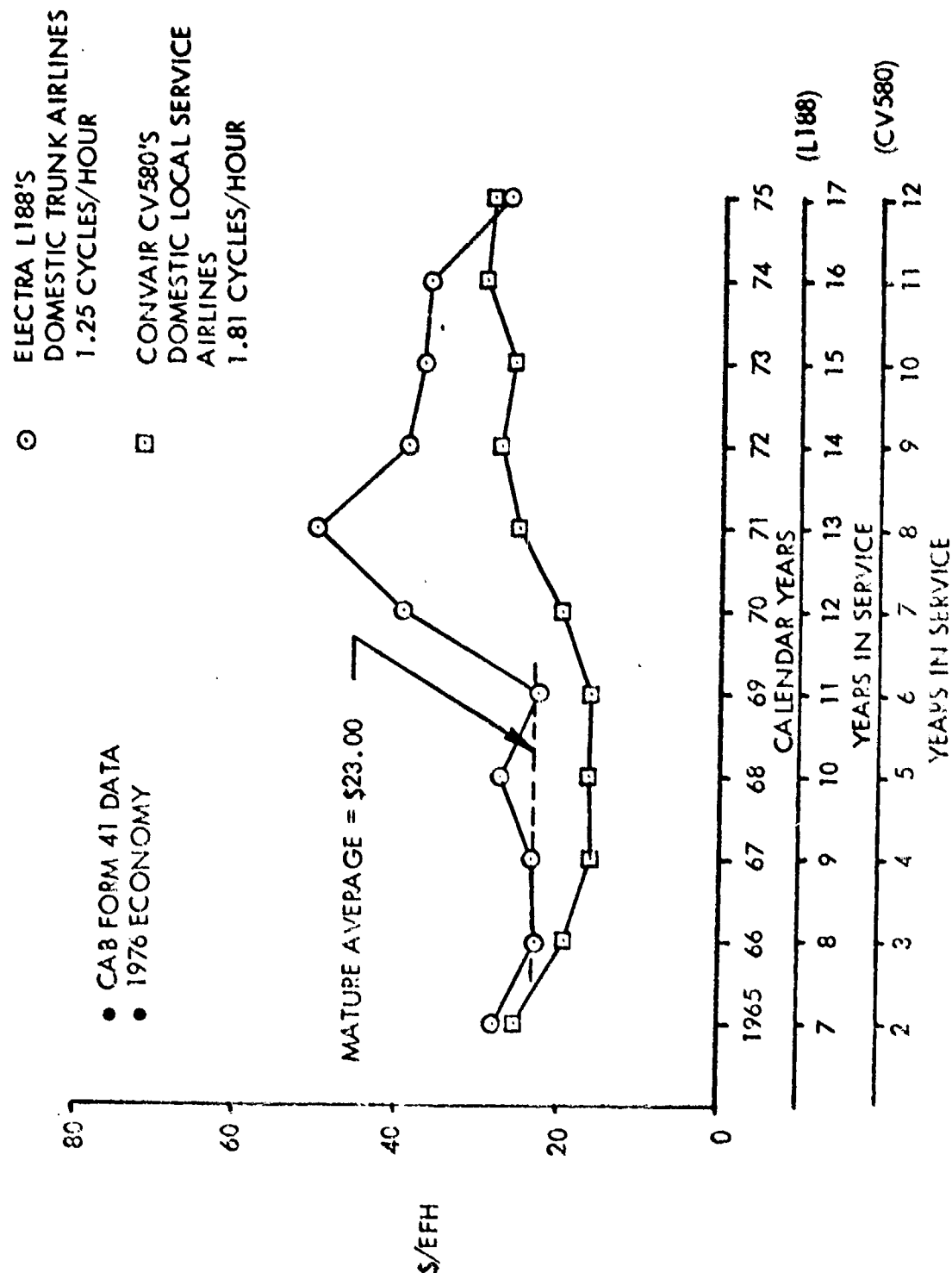


Figure 3.3.1-1. Direct cost per engine flight hour - 501-D13 engine and gearbox

Table 3.3.1-II

Convair CV580 Operators - Domestic Local Service Airlines

| CY | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 |
|---------------|------|------|------|------|------|------|------|------|------|------|------|
| Airline | | | | | | | | | | | |
| Allegheny | X | X | X | X | X | X | X | X | X | X | X |
| Frontier | X | X | X | X | X | X | X | X | X | X | X |
| Lake Central | | | X | X | | | | | | | |
| North Central | | | X | X | X | X | X | X | X | X | X |

Figure 3.3.1-1 shows direct maintenance cost expressed in CY 1976 economy. The data obtained at Eastern Airlines, reference Table 3.2.3.3.1-I contained labor hours and labor dollars for the period from CY 1967 to CY 1976. Eastern also provided their estimated material escalation costs over this period of years. Using this data, escalation rates in terms of the 1976 economy were computed and are shown in Table 3.3.1-III.

Table 3.3.1-III

Economic Escalation Factors

| <u>Year</u> | <u>Labor</u> | <u>Material</u> |
|-------------|--------------|-----------------|
| 1976 | 1.000 | 1.000 |
| 1975 | 1.080 | 1.070 |
| 1974 | 1.182 | 1.145 |
| 1973 | 1.241 | 1.225 |
| 1972 | 1.315 | 1.286 |
| 1971 | 1.500 | 1.351 |
| 1970 | 1.548 | 1.418 |
| 1969 | 1.763 | 1.461 |
| 1968 | 1.986 | 1.505 |
| 1967 | 2.107 | 1.550 |
| 1966 | 2.300 | 1.597 |
| 1965 | 2.368 | 1.644 |

The factors for labor in 1965 and 1966 were extrapolated from data in Reference 1, while 3% per year was applied to obtain the 1965 and 1966 material factors.

A split of labor, material, and outside services for the data shown in Figure 3.3.1-1 was obtained through an independent computer service. The escalation factors were applied directly to the labor and material costs. The material escalation factors were also applied to outside service costs, consistent with the reasoning in Reference 1. A summation of the escalated labor, material, and outside service costs produced the curves shown in Figure 3.3.1-1.

The breakdown of the data in Figure 3.3.1-1 is shown in Figures 3.3.1-2 and 3.3.1-3, expressed in percentages for labor, material, and outside services.

The Electras were introduced into airline service in January 1959, approximately 5-1/2 years before the CV580 went into service. A gas turbine engine typically matures in a period 8 to 11 years after introduction into service. This fact is discussed in Section II of Reference 1, which is a comprehensive discussion of gas turbine engine maintenance costs and their trends. In Figure 3.3.1-1 the maintenance costs for the 501-D13 engine and gearbox show the typical maturing trend in the 8 to 11 year period. Some aberrations from a smooth curve, such as the rise in cost in CY 1968, have been caused by the fact that some of the airlines were phasing out their Electra operations, which affected maintenance policies. In 1968, the last full year of American Airlines operation, their reported engine maintenance costs were double those of previously reported years. Figure 3.3.1-4 shows the rapid reduction in engine flight hours as all airlines except Eastern phased out their Electras after CY 1967. After CY 1970 Eastern was the only trunk airline operating Electras. While maintenance costs typically rise after maturity, the relatively rapid rise of Electra powerplant costs is believed due to the low utilization and the standby type of operation to which Eastern subjected the powerplants in those later years.

From Figure 3.3.1-1, a mature engine, gearbox, and QEC direct maintenance cost per flight hour of \$23.00 in a CY 1976 economy was selected. It should be noted that this cost corresponds to an engine cyclic time of 0.80 hours per flight, or 1.25 cycles per flight hour.

Typical airline operation of the Electra was for average flights of 0.8 hours each. On a per flight hour basis the reciprocal of 0.8 gives 1.25 flights, or trips, per flight hour, which means that the engine is put through a complete operating or duty cycle 1.25 times per engine flight hour. Historical reliability and maintenance cost data (Reference 7) shows that as the number of duty cycles per flight hour increases, the engine maintenance costs increase on a flight hour basis. This is a result of the fact that the engine is operated a greater percentage of the flight hour at higher power or thrusts (take-off and climb at higher temperatures and pressures) than for engines operating over longer flight lengths and fewer cycles per flight hour. For turboprop systems, the propeller maintenance costs also increase with the number of duty cycles but only for non-inherent reasons of Foreign Object Damage (FOD) to the blades and anti-icing heaters where exposure to ground operation causing these condi-

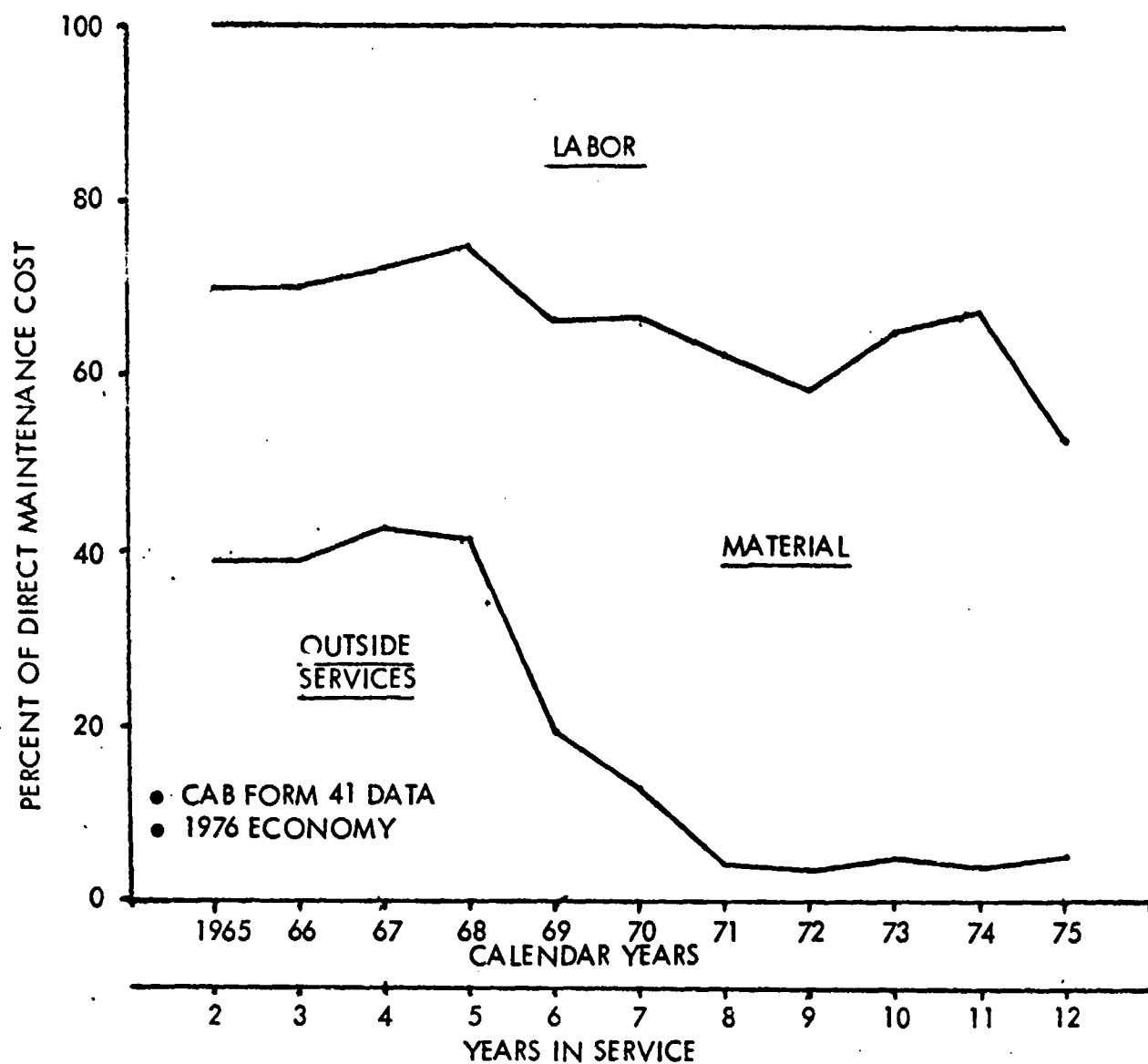


Figure 3.3.1-2. Direct maintenance cost breakdown - 501-D13 engines/Electra airplanes

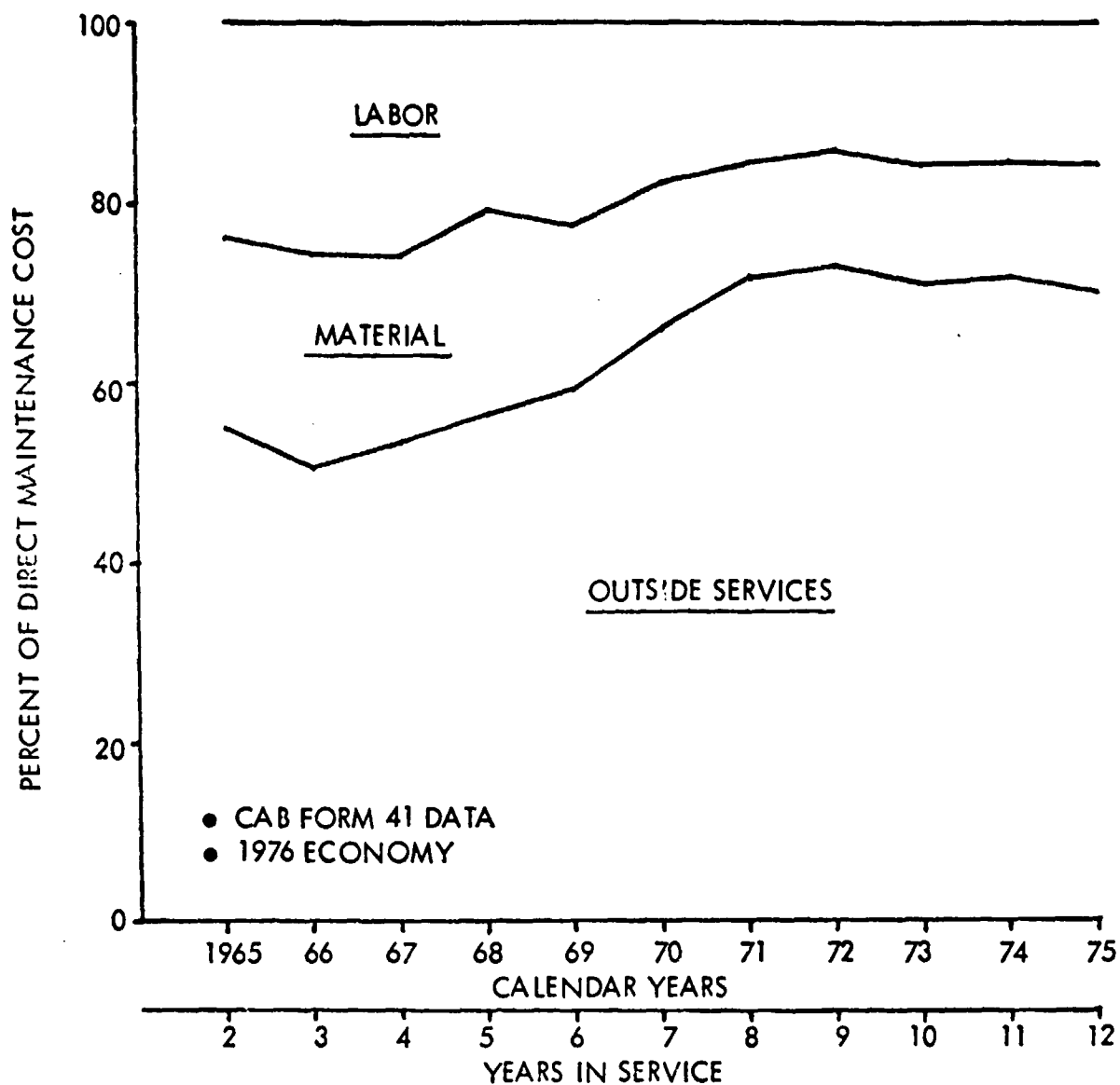


Figure 3.3.1-3. Direct maintenance cost breakdown - 501-D13 engines/CV580 airplanes

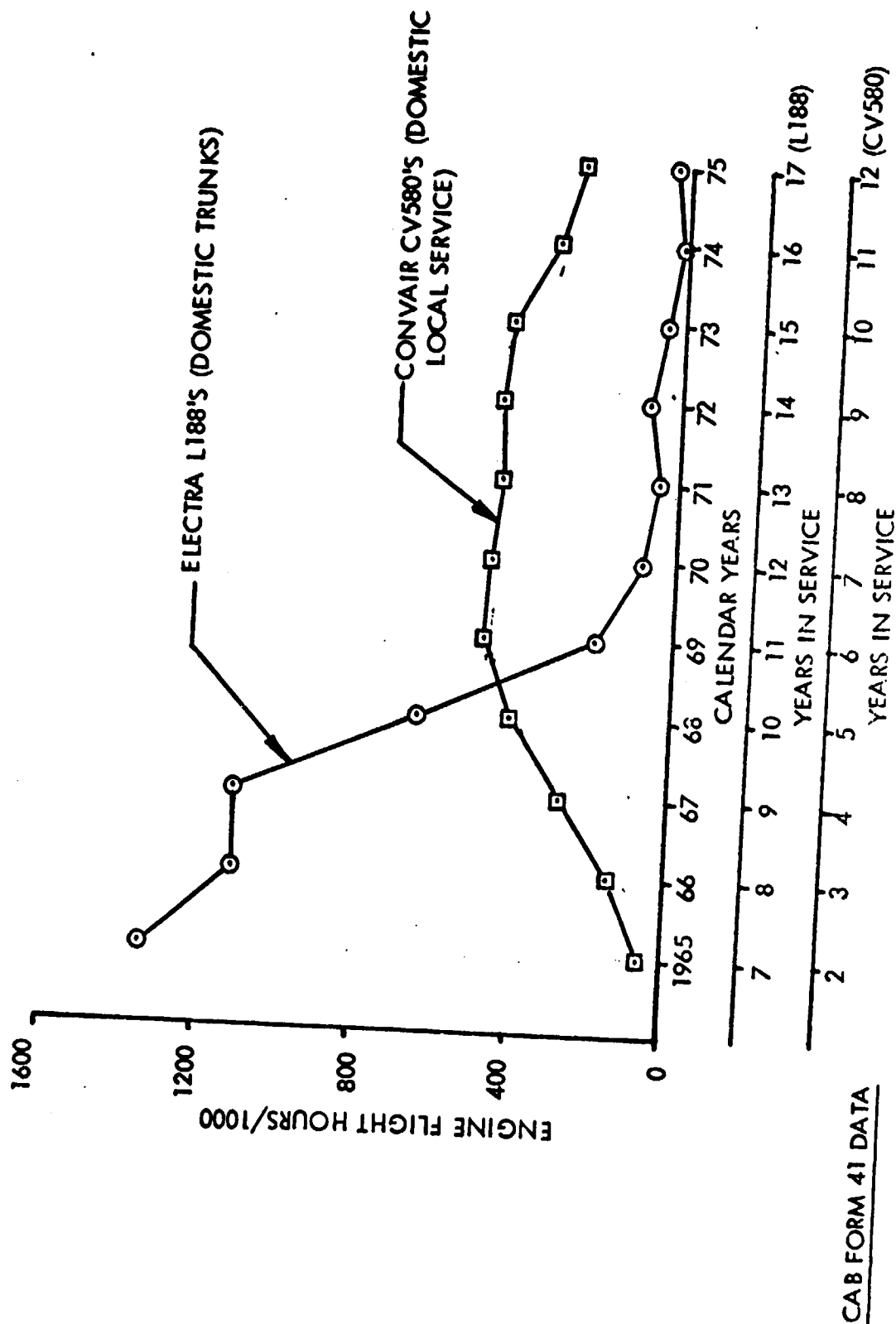


Figure 3.3.1-4. Engine flight hours - 501-D13 engines and gearboxes

tions is increased with increased numbers of duty cycles. Following is a comparison of the turboprop duty cycle for the Electra and CV580 operation of this study.

| | <u>Average Flight Time per Trip, hrs.</u> | <u>Duty Cycles per Flight Hour</u> |
|---|---|--|
| Electra L188's Domestic Trunks | 0.80 | 1.25 |
| Convair CV580's Domestic Local Service | 0.55 | 1.81 |

Figure 3.3.1-1 shows that the cost per flight hour of the 501-D13 powerplant in the Convair CV580's is less than that in the Electras on a calendar year basis. This results from the fact that the CV580 engines are five to six years newer than those of the Electra, and they are also benefiting from the previous service experience and maturity resulting from operation in the Electras. Although the CV580 engines would appear to have matured in a 4 to 6 year period from service introduction, their record has been biased favorably by the previous Electra engine experience.

The Convair CV580 costs can be compared to those of the Electra on an equal years in service basis. On this basis Figure 3.3.1-1 shows that the costs in the CV580 would be slightly higher than those in the Electra. This may reflect the difference in cyclic usage between the two airplanes, where the CV580 powerplant has a duty cycle of 1.81 cycles/flight hour compared to 1.25 cycles/flight hour of the Electra powerplant.

The maintenance costs per engine flight hour that have been discussed are direct maintenance costs as reported on CAB Form 41. The direct maintenance costs include outside service charges, as shown in Figures 3.3.1-2 and 3.3.1-3. The outside services include burden in their charges to the airline. The effect of applying full burden, and removing all burden is shown in Figure 3.3.1-5. Full burden was applied by adding twice the labor expense reported in CAB Form 41 data. (Reference 7). Burden was removed from outside service expense by assuming that 36 percent of outside service is burden, which is a generally accepted percentage in the industry. The fully burdened cost per engine flight hour is \$39.10 compared to the \$23.00/EFH direct maintenance cost. The corresponding unburdened cost is \$19.60/EFH.

In summary, a mature engine direct maintenance cost per flight hour of \$23.00 is believed representative of the 501-D13 engine and gearbox, based upon a duty cycle of 1.25 cycles per engine flight hour. Corresponding fully burdened and unburdened costs are \$39.10 and \$19.60 respectively. These values will be the basis for further comparisons with turbofans and the advanced turboprop.

3.3.2 Propeller

To complete the cost of the total turboprop propulsion system, the cost of the propeller must be added to that of the engine, gearbox, and QEC that was determined in Section 3.3.1.

As noted earlier in the report, propeller costs were not specifically identified in published CAB data. Therefore a propeller cost had to be determined based upon removal rates and overhaul and repair costs obtained from the airlines, repair facilities, and DDA.

3.3.2.1 Aeroproducts 606 Propeller

As noted earlier in this report, maintenance cost data for the 606 propeller on Frontier Airlines CV580's were not available. However, sufficient data was collected during this study to develop an estimate of the Frontier propeller cost by using the reported frequencies of maintenance actions from Frontier 1976 records (reference section 3.2.3.1.2) and the average charges for the various actions as reported from overhaul and repair records (reference Table 3.2.4.2-I). A summary of the propeller cost estimated in this fashion is presented in Table 3.3.2.1-I. As noted in the table, the 606A propeller system shop cost per flight hour is \$5.82 in 1976 economy.

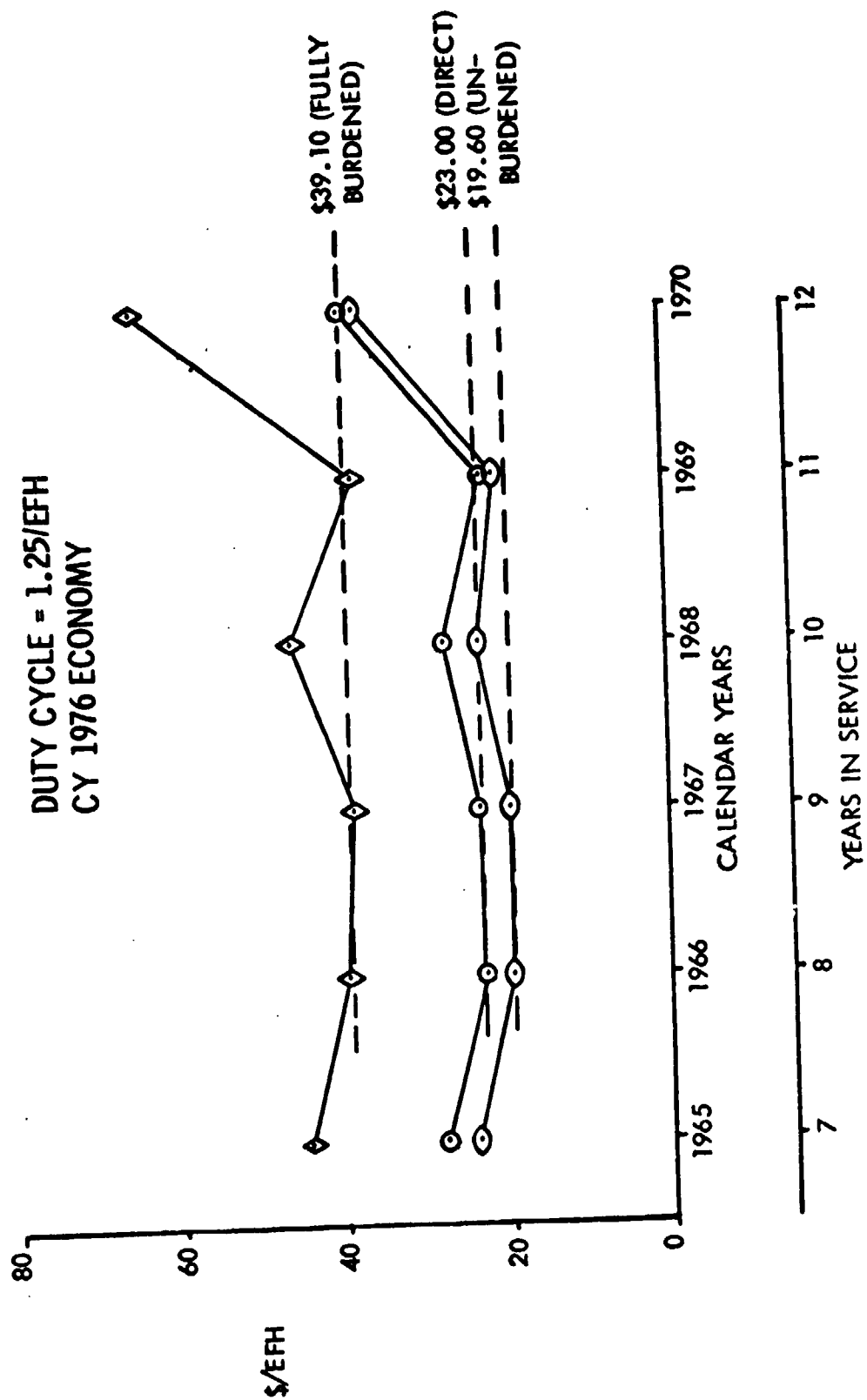


Figure 3.3.1-5. Direct, fully burdened, and unburdened mature maintenance costs - 501-D13 engines/L-188 airplanes

In addition to Aeroproducts 606 propeller maintenance cost data collected during this study (reference sections 3.2.1, 3.2.3.3.2 and 3.2.4.2) and the developed propeller maintenance cost at Frontier Airlines as noted above, two other pieces of cost information were available based on data received from airlines during previous studies conducted by Hamilton Standard:

- Allegheny Airlines CV580, 1974 data.
- Eastern Airlines Electra, 1973 data.

These data were included in the evaluation of the Aeroproducts 606 propeller data collected during this study and the developed Frontier propeller data which lead to establishing a baseline for the 606 propeller maintenance cost. All of the data was converted to 1976 economy utilizing the escalation factors as presented in Table 3.3.1-III. The data is summarized in table 3.3.2.1-II.

TABLE 3.3.2.1-I
DEVELOPED
FRONTIER AIRLINES CV580/606 PROPELLER
MAINTENANCE COST
(SHOP ONLY)

| <u>PROPELLER COMPONENT</u> | <u>Removals per 1000 Propeller Flight Hours</u> | <u>Average Shop Cost, 1976 \$</u> | <u>1976 \$ Per Propeller Flight Hour</u> |
|--------------------------------|---|---------------------------------------|--|
| <u>Prop. Assy</u> | | | |
| Overhaul | 0.094 | \$11,459 | \$1.07 |
| Interim Inspection | 0.200 | 2,500 | .50 |
| Repair | 0.120 | 5,612 | .67 |
| <u>Blades</u> | | | |
| Overhaul | 0.027 | 1,725 | .05 |
| Repair | 0.241 | 975 | .23 |
| <u>Control Unit</u> | | | |
| Overhaul | 0.134 | 8,370 | 1.12 |
| Repair | 0.308 | 2,556 | .79 |
| <u>Components</u> | 5.221 | 266 | <u>1.39</u> |
| TOTAL | | | \$5.82 |

Table 3.3.2.1-II

SUMMARY OF 606 COMMERCIAL
PROPELLER MAINTENANCE COST DATA
(SHOP ONLY)

| <u>Airline</u> | <u>Aircraft</u> | <u>Data Period</u> | <u>Daily A/C Utilization</u> | <u>Propeller Flight Hours</u> | <u>Propeller Premature Removal Rate</u> | <u>1976 \$ Per Propeller Flight Hour</u> | | |
|----------------|-----------------|------------------------|----------------------------------|---------------------------------------|---|--|--------------|--------------|
| | | | | | | <u>Parts</u> | <u>Labor</u> | <u>Total</u> |
| Allegheny | CV580 | 1/66-9/66 | 6.17 | 36,288 | 1.35 | 8.62 | 2.32 | 10.94 |
| | | 1974 | 2.71 | 79,182 | N/A | 4.60 | 2.16 | 6.76 |
| American | Electra | 1965 | 6.72 | 235,388 | .89 | 3.44 | 4.78 | 8.22 |
| | | 1/66-9/66 | 6.40 | 167,712 | .93 | 3.51 | 4.37 | 7.88 |
| Braniff | Electra | 1965 | 7.49 | 98,380 | .68 | 3.39 | 4.55 | 7.94 |
| | | 1/66-9/66 | 8.09 | 79,548 | .53 | 3.29 | 4.00 | 7.29 |
| Eastern | Electra | 1965 | 7.13 | 405,318 | .92 | 7.41 | .88 | 8.29 |
| | | 1/66-9/66 | 5.96 | 253,873 | .64 | 3.18 | .76 | 3.94 |
| | | 1/68-12/69 | N/A | 343,856 | N/A | 5.74 | 1.33 | 7.07 |
| | | 1973 | 2.95 | 68,976 | N/A | 5.33 | 2.73 | 8.06 |
| | | 1974 | 1.84 | 41,992 | 1.60 | 12.08 | 4.60 | 16.68 |
| | | 1975 | 1.99 | 43,536 | 1.47 | 10.63 | 4.69 | 15.32 |
| | | 1/76-11/76 | 2.17 | 43,568 | 1.12 | 5.65 | 2.20 | 7.85 |
| Frontier | CV580 | 1965 | 7.83 | 54,928 | .86 | 7.43 | 2.53 | 9.96 |
| | | 1/66-9/66 | 8.67 | 74,134 | .94 | 1.93 | 3.22 | 5.15 |
| | | 1/76-7/76 | N/A | 74,702 | .67 | | | 5.82 |
| National | Electra | 1965 | 7.92 | 196,604 | .98 | 4.40 | 5.40 | 9.80 |
| | | 1/66-9/66 | 6.17 | 114,452 | .93 | 4.60 | 5.50 | 10.10 |
| Pacific | | | | | | | | |
| Southwest | Electra | 1965 | 8.02 | 70,286 | .71 | 5.64 | 3.58 | 9.22 |
| Western | Electra | 1965 | 7.11 | 124,544 | .73 | 5.43 | 2.37 | 7.80 |
| | | 1/66-9/66 | 7.57 | 99,134 | .48 | 2.97 | 1.61 | 4.58 |

N/A - Not Available

The maintenance cost values per propeller flight hour in 1976 economy were grouped by aircraft type and data base. Figure 3.3.2.1-1 displays the results of the analysis which indicates a weighted average shop maintenance cost for 606 propellers of \$7.81 per propeller flight hour. The weighted average value was developed by summing all propeller costs in 1976 economy and dividing by the sum of the propeller hours accumulated for all data bases.

The data was then reviewed more closely to better understand the wide variation in reported maintenance cost, from \$3.94 to \$16.68 per propeller flight hour. The following data points were rejected for the reasons noted:

1. Allegheny, 1/66-9/66. The costs in this data period include a large cost for parts supplied to Allegheny. This cost was amortized over the nine months of the data period thus inflating the cost per hour. The fleet was increasing rapidly during this period and it is hypothesized that the substantial parts charge reflects the acquisition of spare parts to support the anticipated needs of the fleet. Thus it should be amortized over some longer period of time. Since the proper period cannot be determined, the data was discarded.
2. Eastern, 1965 and 1/66-9/66. The data, which is based on records of DDA shop charges only, does not include all propeller charges since Eastern was performing some of its own shop maintenance. Thus the cost per propeller hour does not represent the actual cost.
3. Eastern, 1973 thru 11/76. Aircraft utilization was extremely low during this period causing an excessive propeller removal rate and hence high maintenance cost per flight hour. The relationship of high per hour maintenance costs with low utilization has been reported by a number of investigators and is an accepted correlation (Reference 8).
4. Frontier, 1965. This is another case like that noted for Allegheny in 1. above.
5. National, 1/66-9/66. Aircraft utilization was extremely low during part of the data period causing increased maintenance cost.

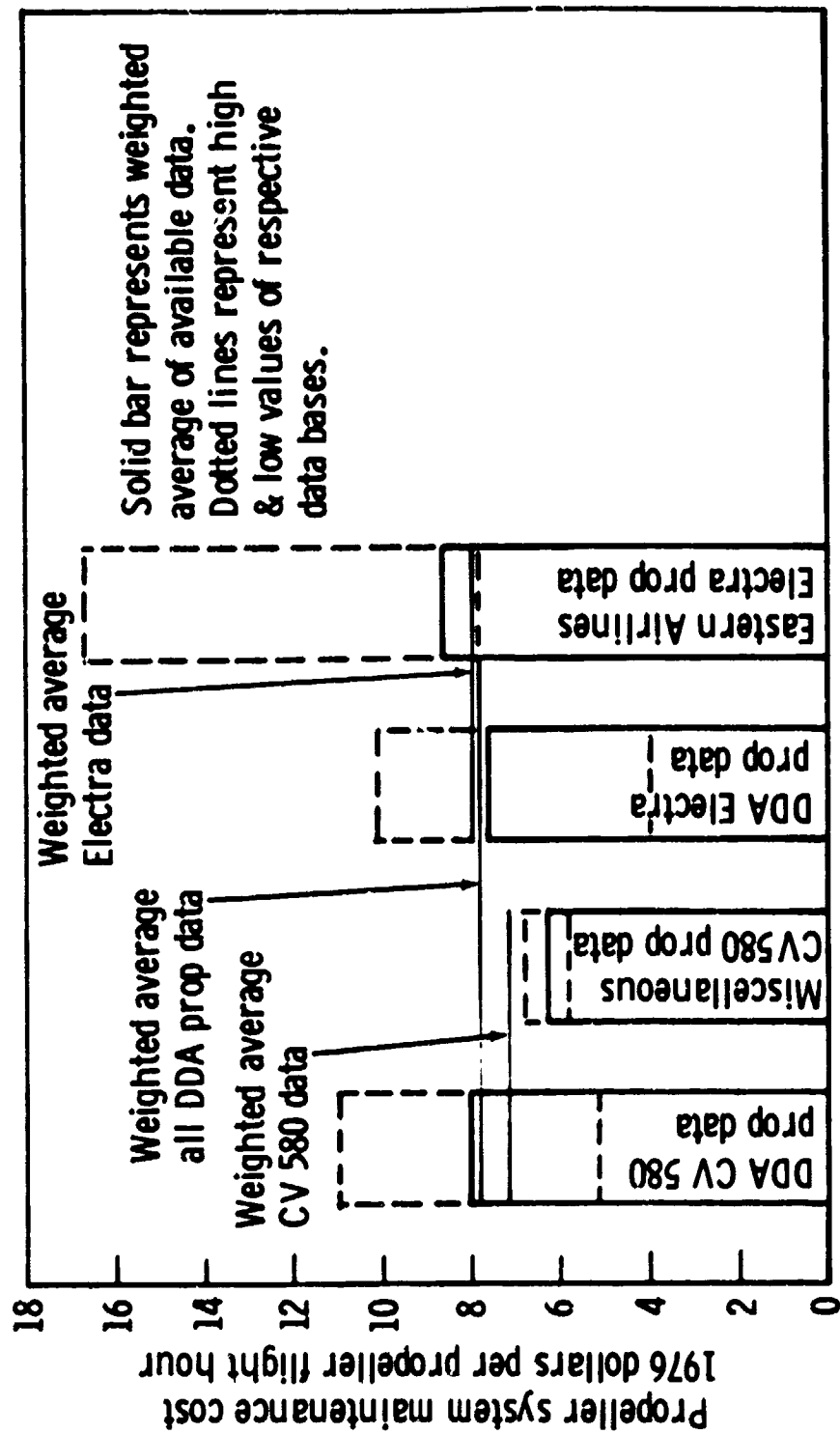


Figure 3.3.2.1-1. Summary of 606 propeller system maintenance cost data.

6. Western 1965 and 1/66-9/66. Western Airlines was not in the Unit Exchange Program. Thus the records of DDA charges do not include all propeller costs and result in an incorrect cost per hour.

Following this analysis, the range of values for the remaining ten data points is from a low of \$5.15 to a high of \$9.80 with a weighted average of \$7.73. This compares closely with the weighted average of all data points of \$7.81 as reported above.

One additional analysis was conducted to isolate cost variations with time and aircraft application. The six Electra propeller data points from the 1965 and 1966 time period were segregated and the weighted average was found to be \$8.48. The two CV580 data points from 1974 and 1976 were also segregated and the weighted average was found to be \$6.30. Thus the average 606 propeller cost expressed in 1976 economy can be seen to have reduced from \$8.48 for the mature Electra operation during the mid-sixties to \$6.30 for the CV580 operation during the mid-seventies.

Based on a review of the above analyses, it was concluded that the Frontier Airlines CV580/606 propeller shop maintenance cost data should be used for the 606 propeller baseline for the following reasons:

- This data is representative of mature propeller operation. The synthesized cost per propeller flight hour of \$5.82 (reference Table 3.3.2.1-1) compares well with the average of available current CV580 propeller cost of \$6.30 (reference Figure 3.3.2.1-1).
- Detail regarding the causes of maintenance actions for current Frontier propeller operations is available. This permits identification of cost drivers.
- The Frontier propeller reliability rates are representative of all available Aeroproducts 606 propeller data collected under this program. This data was assembled and grouped by aircraft type and data base and is summarized in bar chart form in Figure 3.3.2.1-2. Note that weighted average values for 606/CV580, 606/Electra, and all 606 data are presented. These values were established by summing all propeller costs and dividing by the sum of the accumulated hours of experience in the respective data bases. The data presented in this form shows that the 606 propeller has performed more reliably on the CV580 than the Electra.

The \$5.82 per propeller flight hour represents shop cost only, as shown in Table 3.3.2.1-I. The remaining element to be added is line labor, which is approximately 10% of the total. Therefore, the total cost of 606 propeller maintenance on the CV580 is \$6.47 ($5.82 \div 0.90$) per propeller flight hour. This figure represents a duty cycle of 1.81 cycles per flight hour. For different duty cycles this cost must be adjusted as explained in Section 3.3.2.2. For the Electra, which has a duty cycle of 1.25 cycles per flight hour, the total cost per flight hour will reduce to \$6.35.

The synthesized propeller maintenance costs represent fully burdened costs because they are based upon shop costs per overhaul or repair from outside repair facilities. To obtain a direct maintenance cost corresponding to direct maintenance as reported on CAB Form 41, it was necessary to unburden the line maintenance costs and add the result to the shop charges from the outside repair facilities. Unburdened line labor was assumed to be 1/3 of the fully burdened labor. To obtain a completely unburdened maintenance cost the outside repair facilities labor and material charges were analyzed and burden charges were removed from the labor portions of the total charges. In the case of the 606 propeller, burden was approximately 34% of the total repair facility shop charges. The resulting direct, fully burdened, and unburdened cost per flight hour of the 606 propeller operating on the Electra at 1.25 cycles per flight hour were as follows:

| | <u>\$/Propeller Flight Hour</u> |
|----------------|---------------------------------|
| Direct | \$5.92 |
| Fully burdened | 6.35 |
| Unburdened | 3.98 |

3.3.2.2 Hamilton Standard 54H60 Propeller

Data regarding commercial experience with the HS 54H60 propeller is limited to that collected at Saturn Airways. Maintenance event data consists only of the reported reason for removal; teardown inspections intended to isolate the cause of failure usually were not conducted. Removals of 54H60 propeller assemblies during 1975 have been tabulated by reason for removal of the propeller systems for both the L-188 and L-382 aircraft. The results are summarized in Tables 3.3.2.2-I and 3.3.2.2-II. respectively.

Solid bar represents weighted avg.
of available data. Dotted lines
represent high & low values of
respective data sources.

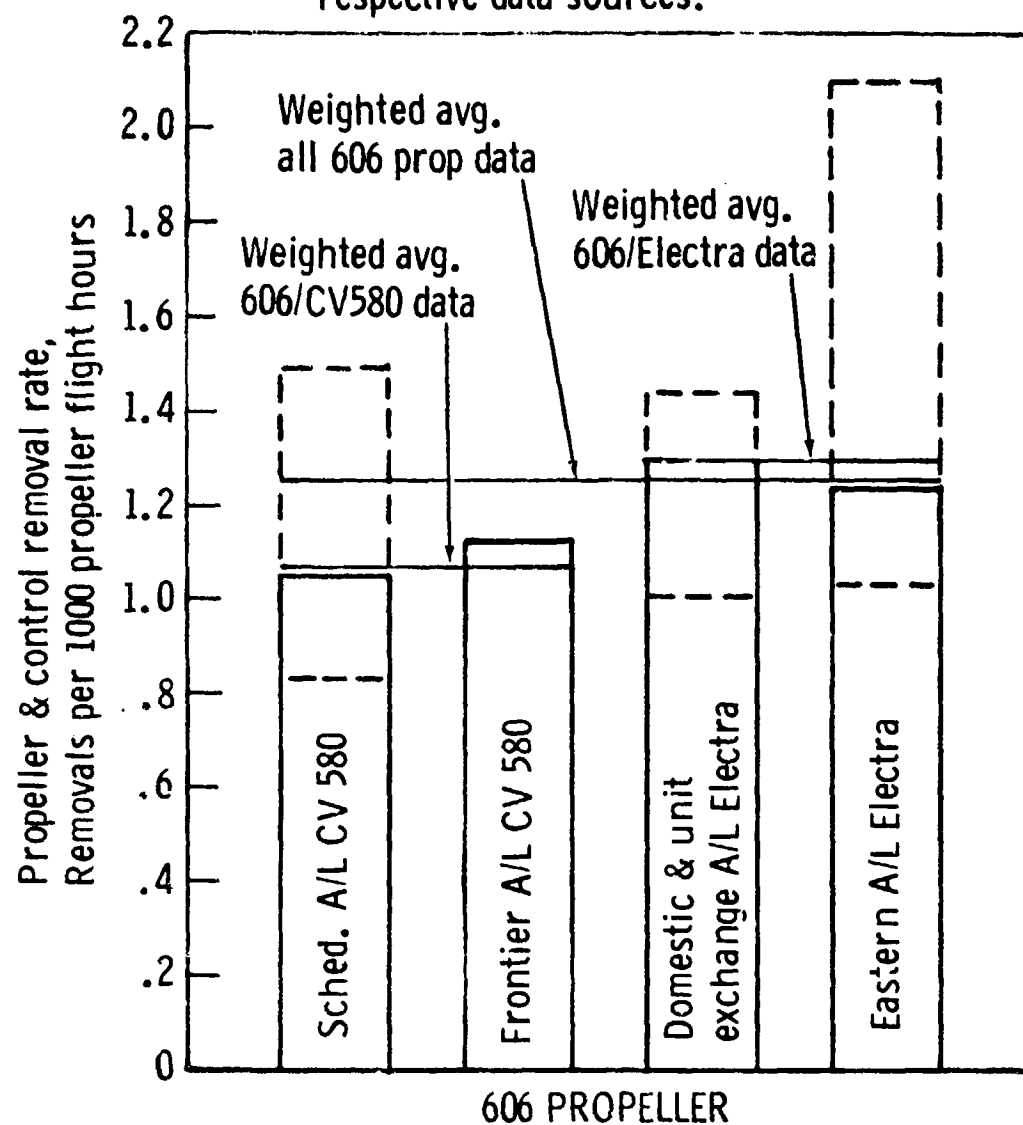


Figure 3.3.2.1-2. Summary of 606 propeller reliability data.

Table 3.3.2.2-I
SUMMARY SATURN AIRWAYS L-188 ELECTRA
54H60 PROPELLER EVENTS DURING 1975

| <u>Reason for Removal</u> | <u>Number of Removals</u> | <u>Removal Rate Removals per 1000 Hrs.</u> |
|---------------------------------|-------------------------------|--|
| Propeller Assembly | | |
| Overhaul | 12 | .135 |
| Blade Cuff Damage | 2 | .023 |
| Vibration | 1 | .011 |
| Loose Boots | 5 | .056 |
| De-ice Heater Problems | 4 | .045 |
| Leakage | 3 | .034 |
| Control Assembly | | |
| Overhaul | 16 | .180 |
| Leakage | 6 | .068 |
| Fails to Unfeather | 2 | .023 |
| Failure to Stay in Feather | 1 | .011 |
| Low Oil Light Indication | 1 | .011 |
| RPM Fluctuations | 1 | .011 |
| Metal Contamination | 1 | .011 |
| Maintenance Damage | 1 | .011 |
| Valve Housing | | |
| Overhaul | 18 | .202 |
| Inoperative | 5 | .056 |
| Failure to Synchronize | 5 | .056 |
| Overspeed | 2 | .023 |
| Sync Servo Inoperative | 2 | .023 |
| Miscellaneous | 14 | .158 |
| Pitchlock Regulator | 20 | .225 |
| Synchrophaser | 38 | .428 |
| Miscellaneous Components | <u>17</u> | <u>.191</u> |
| TOTAL (1) | 139 | 1.564 |
| TOTAL (2) | .93 | 1.047 |

(1) Synchrophaser not incl. in total, one only required per aircraft.

(2) Unscheduled removals only without synchrophaser.

Table 3.3.2.2-II

SUMMARY OF SATURN AIRWAYS L-382 HERCULES
54H60 PROPELLER EVENTS DURING 1975

| <u>Reason for Removal</u> | <u>Number of Removals</u> | <u>Removal Rate Removals per 1000 Hrs.</u> |
|-------------------------------------|-------------------------------|--|
| Propeller Assembly | | |
| Overhaul | 11 | .068 |
| Blade Cuff Damage | 2 | .012 |
| Vibration | 3 | .019 |
| Loose Boots | 2 | .012 |
| De-ice Heater Problems | 10 | .062 |
| Fails to Unfeather | 4 | .025 |
| Unknown | 3 | .019 |
| Metal Contamination | 1 | .006 |
| Blade Tip Damage | 1 | .006 |
| Control Assembly | | |
| Overhaul | 18 | .111 |
| Leakage | 1 | .006 |
| Fails to Unfeather | 7 | .043 |
| Low Oil Light Indication | 2 | .012 |
| Miscellaneous | 8 | .049 |
| Valve Housing | | |
| Overhaul | 15 | .092 |
| Inoperative | 7 | .043 |
| Failure to Synchronize | 4 | .025 |
| Overspeed | 1 | .006 |
| Fails to Terminate Feather | 6 | .037 |
| Beta Shaft Binding | 2 | .012 |
| Low Oil Light | 2 | .012 |
| RPM Fluctuation | 3 | .019 |
| Miscellaneous | 9 | .055 |
| Pitchlock Regulator | 11 | .068 |
| Synchrophaser | 57 | .351 |
| Miscellaneous Components (2) | 31 | .191 |
| TOTAL (1) | 164 | 1.010 |
| TOTAL (3) | 120 | 0.739 |

(1) Synchrophaser not included in total, one only required per aircraft.

(2) Based on Saturn Electra removal rate.

(3) Un-scheduled removals only without synchrophaser.

A comparison of the L-188 and L-382 propeller system removal rates of 1.564 and 1.010 indicates the later model 54H60 propeller used on the L-382 offers more reliable performance over the earlier model used on the L-188. Furthermore, the majority of Saturn L-188 airframes, which were initially used in CY1956, now have 35,000 to 36,000 total hours. The L-382 airframes, first used in CY1965, range from 5,000 to 28,000 total hours with the majority in the 17,000 to 19,000 hour range. Thus the present L-382 hardware performance is representative of operational maturity while the L-188 performance is indicative of a period of wear-out. It was concluded that the L-382 experience should be used for the baseline 54H60 since it is representative of mature operation.

To establish HS 54H60 propeller baseline maintenance cost it was necessary to develop the cost per hour based on the Saturn frequencies of maintenance actions and the average costs per maintenance action (reference Table 3.2.3.2.2-II). A summary of the L-382 propeller costs is presented in Table 3.3.2.2-III as a sample of estimating the cost in this fashion. The maintenance cost of the Electra (L188) propeller was developed in the same manner. Note that all dollar values are expressed in 1976 economy based on escalation factors per Table 3.3.1-III.

In addition to the L188 Electra and L-382 Hercules costs as developed above, an estimate of \$2.73 per propeller flight hour for the L-382 propeller based on data from the period 10/75 thru 9/76 was received from the Saturn Finance Department. No breakdown of this cost was available. A summary of all the acquired commercial HS propeller data including the data from the Saturn Financial Department is presented in Table 3.3.2.2-IV.

The weighted average maintenance cost of all the data is \$2.79 per propeller flight hour, with a range from \$2.36 to \$3.68. Based on discussions with personnel from the propeller overhaul and repair agencies and Saturn Airlines Engineering Department it was learned that the cost to maintain the L-188 propeller hardware has been increasing due to the age of the equipment. Thus the L-188 propeller cost per flight hour was eliminated from consideration in establishing the HS 54H60 propeller baseline as not being representative of a mature propeller system and also because of its poorer reliability. It was then concluded that the L-382 propeller data from 1975 should be used as the baseline for HS propeller maintenance cost. This data is considered representative of mature HS commercial propeller maintenance costs for the following reasons:

Table 3.3.2.2-III

SATURN AIRLINES L-382 HERCULES 54H60
PROPELLER MAINTENANCE COST
(SHOP ONLY)

| <u>PROPELLER COMPONENT</u> | <u>Removals per 1000 Propeller Flight Hours*</u> | <u>Average Shop Cost, 1976 \$</u> | <u>1976 \$ per Propeller Flight Hour</u> |
|--------------------------------|--|---------------------------------------|--|
| <u>Prop. Assy</u> | | | |
| Overhaul | 0.068 | \$9,515 | \$.65 |
| Repair | 0.160 | 3,435 | .55 |
| <u>Control Unit</u> | | | |
| Overhaul | 0.111 | 3,241 | .36 |
| Repair | 0.111 | 1,772 | .20 |
| <u>Valve Housing</u> | | | |
| Overhaul | 0.092 | 2,696 | .25 |
| Repair | 0.209 | 639 | .13 |
| <u>Pitchlock Reg.</u> | 0.068 | 561 | .04 |
| <u>Synchrophaser</u> | 0.350 | 321 | .11 |
| <u>Components</u> | 0.191 | 379 | <u>.07</u> |
| TOTAL | | | \$2.36 |

*Based on 162,454 propeller flight hours

- The time in service and the time accumulated on the airframes as of the time of the data period are indicative of a mature system.
- The data base from which the maintenance cost has been developed is comparable in size to the propeller data bases for other data points including the 606 in that a total of 162,454 propeller hours were accumulated.
- The aircraft utilization was high during the data period.

TABLE 3.3.2.2-IV

SUMMARY OF HAMILTON STANDARD 54H60
COMMERCIAL PROPELLER MAINTENANCE COST DATA
(SHOP ONLY)

| <u>Airline</u> | <u>Aircraft</u> | <u>Data Period</u> | <u>Daily A/C Util.</u> | <u>Propeller Flight Hours</u> | <u>Cost per Propeller Flight Hour</u> | |
|----------------|----------------------|------------------------|--------------------------------|---------------------------------------|---|----------------|
| | | | | | <u>Then Yr. \$</u> | <u>1976 \$</u> |
| Saturn | Electra (L-188) | 1975 | 6.7 | 88,858 | \$3.42 | \$3.68 |
| | Hercules (L-382) | 1975 | 9.4 | 162,454 | 2.18 | 2.36 |
| | Hercules* (L-382) | 10/75-9/76 | 9.4 | 163,598 | 2.73 | <u>2.73</u> |
| | WEIGHTED AVERAGE | | | | | \$2.79 |

*Saturn Financial Department Data

For purposes of adding propeller cost to engine cost to develop total propulsor cost, it is necessary to adjust the HS propeller data to reflect the engine duty cycle. At Hamilton Standard commercial propellers are designed for infinite life; thus inherent failure rates are not affected by changes in duty cycle. However, the non-inherent failure rate associated with Foreign Object Damage (FOD) and heater problems are directly proportional to the number of flights per hour since exposure to the conditions causing these failures is proportional to the number of flights per hour.

The propeller assembly events on the L-382 during 1975 (reference Table 3.3.2.2-II) were reviewed to establish the number of events of FOD and heater failure with the following results:

| | |
|------------------------|----------|
| Blade Cuff Damage | 2 |
| De-Ice Heater Problems | 10 |
| Blade Tip Damage | <u>1</u> |
| TOTAL | 13 |

The Frontier Airlines CV580 mission was chosen as the base for purposes of adjusting the above number of HS propeller events. During 1975, the Frontier CV580 aircraft average flight time was 0.55 hour while the Saturn L-382 during 1975 and 1976 had an average flight time of 2.20 hours. Then the adjustment factor for the 13 events is 4 ($2.2/0.55 = 4.0$). Thus the Saturn L-382 propeller would have been expected to experience 52 FOD and heater events if flown to the Frontier duty cycle. This is equivalent to an increase in the propeller assembly repair rate of 0.240 repairs per 1000 propeller hours. Assuming the average cost per repair of \$3,435 (reference Table 3.3.2.2-III), the increase in maintenance cost per propeller hour is \$0.83 per hour. Then the HS propeller baseline shop maintenance cost is \$3.19 per propeller hour based on Frontier Airlines CV580 duty cycle of .55 hour per flight or 1.81 cycles per flight hour. The remaining element to be added is line labor, which is approximately 10% of the total. Therefore, the total cost of 54H60 propeller maintenance at the CV580 duty cycle is \$3.54 ($3.19 \div 0.90$) per propeller flight hour. For the Electra, which has a duty cycle of 1.25 cycles per flight hour, the total cost per per flight hour will reduce to \$3.20.

As explained in Section 3.3.2.1 the synthesized propeller costs per flight hour are fully burdened. Similarly to the reasoning in Section 3.3.2.1 the fully burdened, the direct, the unburdened 54H60 propeller costs per flight hour at the Electra duty cycle are as follows:

| | <u>\$/Propeller Flight Hour</u> |
|---------------------|---------------------------------|
| Direct Cost | \$2.99 |
| Fully Burdened Cost | 3.20 |
| Unburdened Cost | 2.11 |

3.3.2.3 Comparison of 606 and 54H60 Propeller Maintenance Costs

From sections 3.3.2.1 and 3.3.2.2, a comparison of Aeroproducts 606 and Hamilton Standard 54H60 propeller maintenance cost can be made. Figure 3.3.2.3-1 depicts this comparison in bar chart form based on the Frontier Airlines CV580 duty cycle.

The maintenance cost values for the respective propellers were analyzed to determine the causes for the nearly two to one difference in dollars per flight hour. Figure 3.3.2.3-2 identifies the sources of the difference in propeller maintenance cost. The cost difference associated with interim inspections occurs as a result of no similar requirement for the 54H60 propeller. This inspection of the 606 propeller assembly, which is required by DDA, is to check for corrosion and race spalling and to reseal the assembly. The cost differences for overhauls and repairs requires further investigation for explanation, as follows.

Overhaul of the 54H60 Propeller Assembly occurred at the rate of 0.068 overhauls per 1000 propeller flight hours versus 0.094 for the 606 propeller assembly (reference Tables 3.3.2.1-I and 3.3.2.2-III). At first this seems inconsistent with the TBO requirements of 6500 and 9000 hours respectively for the 54H60 and 606 propellers. However, the number of units that reach overhaul is a function of the number of units that fail as well as the TBO; the higher the failure rate the fewer units that reach TBO. Review of the propeller assembly repair rates indicates

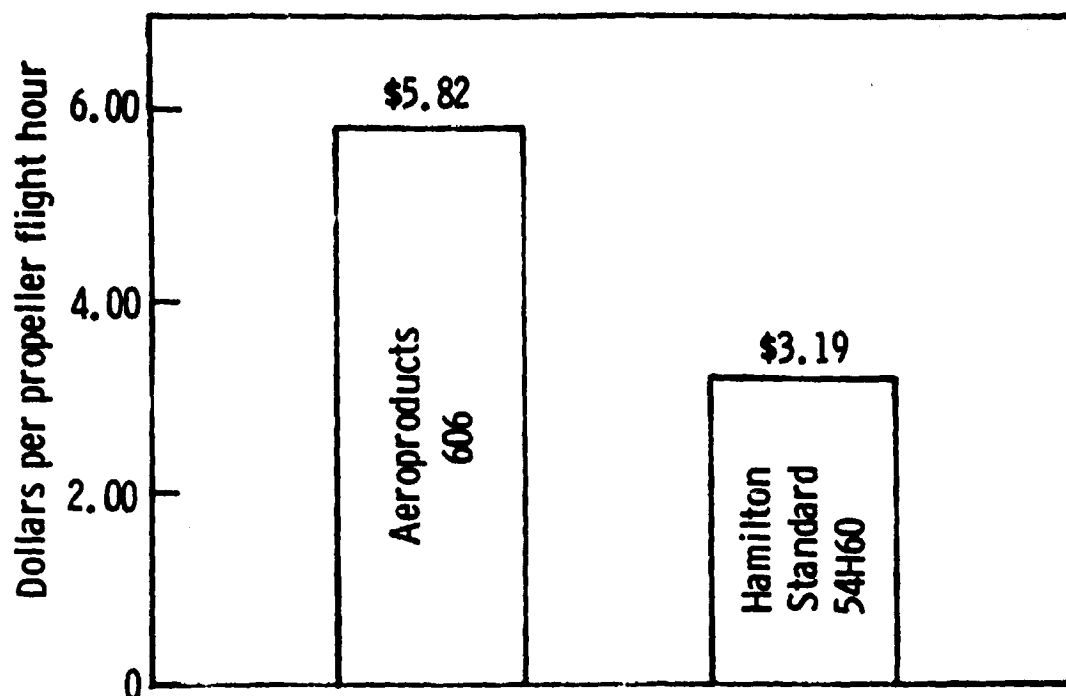


Figure 3.3.2.3-1. Comparison of Aeroproducts 606 and Hamilton Standard 54H60 propeller shop maintenance costs.

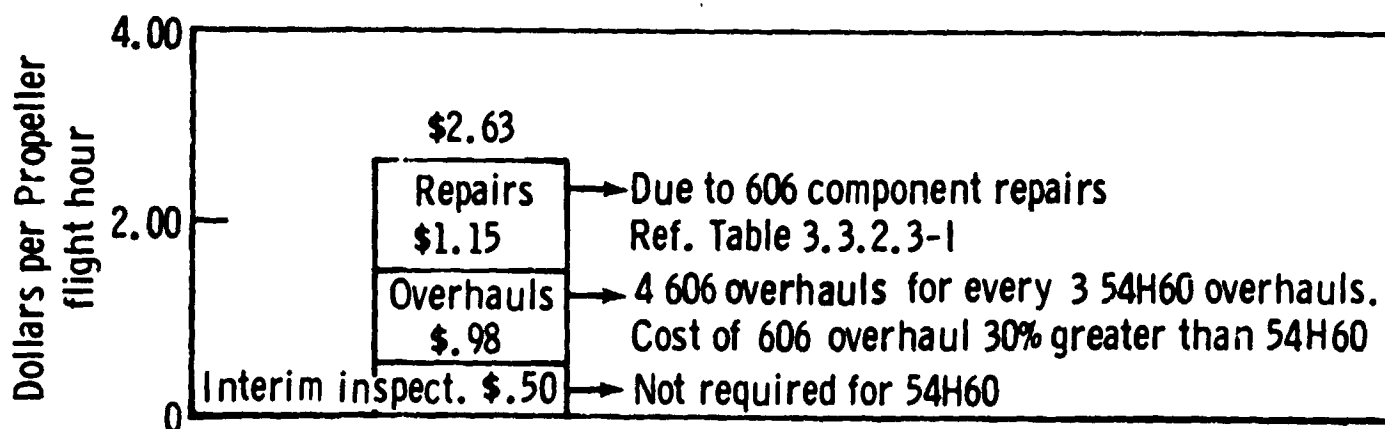


Figure 3.3.2.3-2. Sources of difference in Aeroproducts 606 and Hamilton Standard 54H60 propeller shop maintenance costs.

a rate of 0.120 for the 606 and 0.400 for the 54H60 at the CV580 duty cycle. The values are such that the rates of overhaul are consistent with the respective assembly TBO's. In addition to a higher rate of overhauls of the 606 versus the 54H60, the 606 propeller overhaul cost is greater by approximately 30 percent. The net result of more frequent as well as more costly overhauls of the 606 propeller accounts for a cost difference of \$0.42 per propeller flight hour. Similarly, the 606 control overhaul costs account for a cost difference of \$0.51 per propeller flight hour. The combined overhaul rate of the two module 54H60 control is greater than the 606 control. However, the dominant factor in this case is the two module 54H60 control overhaul cost of \$3,241 or \$2,696 for the control unit or valve housing respectively versus the single module 606 control overhaul cost of \$8,370 (reference Tables 3.3.2.1-I and 3.3.2.2-III). The balance of the difference in overhaul cost of \$0.05 per propeller flight hour is due to 606 blade overhauls for which there is no counterpart in the 54H60 propeller.

An examination of propeller assembly repair costs indicates the 54H60 assemblies cost \$0.06 more per propeller flight hour than the comparable 606 assemblies. This relatively small difference is the net result of a substantially higher 54H60 propeller assembly removal rate, a nearly equal removal rate for controls and a lower cost per repair for 54H60 assemblies in all cases. However, examination of the propeller component repair costs reveal the 606 components cost \$1.21 more per propeller flight hour for a net repair cost difference of \$1.15 per propeller flight hour for the 606 propeller. The component repair costs were

examined to identify the sources of this cost difference. Some examples are shown in Table 3.3.2.3-I which indicate that features unique to the 606 propeller and high removal rates explain the bulk of the cost difference.

The Hamilton Standard 54H60 propeller has been selected as the propeller system to use for purposes of establishing current turboprop propulsion system maintenance costs. The primary reasons are:

- The Hamilton Standard 54H60 propeller system which is still in production has experienced an on-going development program to correct deficiencies. Consequently, the 54H60 system is more representative of the maintenance cost levels which are being achieved for existing propellers.
- Later in this report, comparisons will be made with projected costs for an advanced system designed by Hamilton Standard. Differences in company design philosophies which can influence maintenance costs will be eliminated by utilizing the 54H60 propeller system as the baseline.

Throughout the remainder of this report, the Hamilton Standard 54H60 propeller system will be used exclusively for current propeller maintenance costs.

Table 3.3.2.3-I
Significant Cost Items
Aeroproducts Components

| <u>Item</u> | <u>\$/Hour</u> | <u>Cost/Repair</u> | <u>Comments</u> |
|-----------------|----------------|--------------------|--|
| Rotary Actuator | .16 | \$270 | Not required in 54H60 |
| Alternator | .05 | \$277 | Not required in 54H60 |
| Sync. Assy. | .36 | \$373 | 54H60 cost per repair is similar. Aeroproducts removal rate is 3 times 54H60 removal rate. |
| Governor Valve | .31 | \$413 | High removal rate (.748 removals per 1000 prop hours). |

3.3.3 Total 501-D13/54H60 Turboprop Propulsion System

The direct, burdened, and unburdened maintenance costs of the mature 501-D13 engine, gearbox and QEC was determined as described in Section 3.3.1. Corresponding costs of the 54H60 propeller were determined as described in Section 3.3.2. Based upon Electra operation where the duty cycle is 1.25 cycles per flight hour, the total mature turboprop propulsion system maintenance cost in CY 1976 dollars is as follows:

501-D13/54H60

| | <u>Cost/Flight Hour</u> | | |
|------------------------------|-------------------------|---------------|-----------------------|
| | <u>Unburdened</u> | <u>Direct</u> | <u>Fully Burdened</u> |
| 501-D13 Engine, Gearbox, QEC | \$19.60 | \$23.00 | \$39.10 |
| 54H60 Propeller | <u>2.11</u> | <u>2.99</u> | <u>3.20</u> |
| TOTAL | \$21.71 | \$25.99 | \$42.30 |

These results are compared in bar chart form in Figure 3.3.3-1.

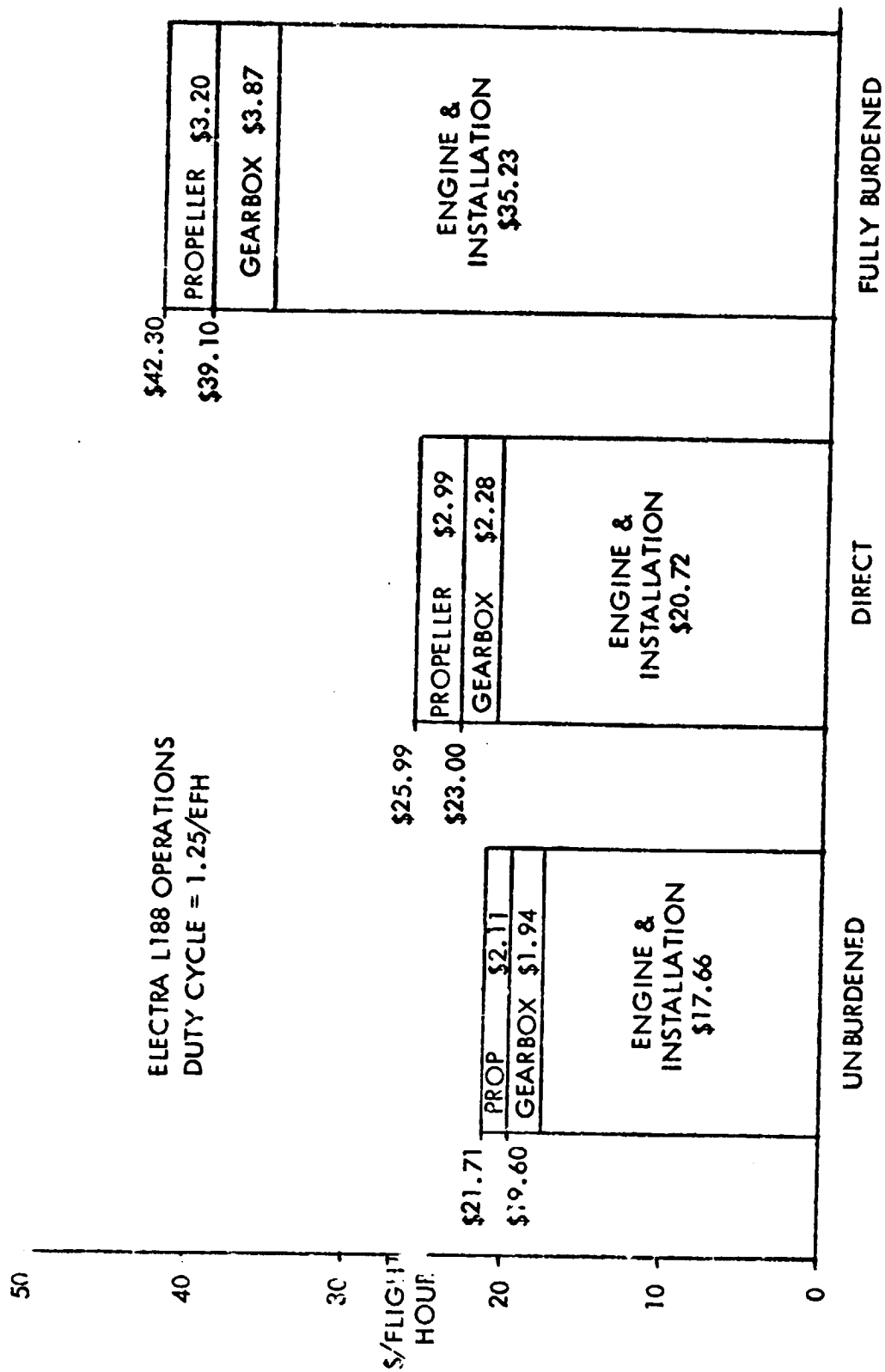


Figure 3.3.3-1. Mature direct, burdened, and unburdened cost per flight hour of the 501-D13/54H60 turboprop systems.

3.4 Comparison With Turbofan Maintenance Costs

The JT8D was chosen for comparison with the turboprop because it is the most widely used turbofan in U. S. domestic service, and it represents current standards for reliability and maintenance in the industry. The JT8D entered airline service in CY 1965 so that it has been in service long enough for it to have established its mature status. In addition it is a widely used turbofan engine in the type of aircraft for which an advanced turboprop would be ideally suited. Data is also shown for the higher bypass systems such as the JT9D, CF6-6, and RB211, but they have not been in service long enough to establish their mature maintenance cost.

3.4.1 JT8D Direct Maintenance Costs

Published CAB Form 41 data was used to establish the mature direct maintenance cost of the JT8D. Domestic trunk airlines operating B727 -100's and domestic local service airlines operating B737's, each using JT8D-1 or -7 engines, were chosen for the comparison. The airlines that were included in these mixes were as shown in Tables 3.4.1-I and 3.4.1-II. Engine flight hours for the two fleets are shown in Figure 3.4.1-1.

Table 3.4.1-I

B727-100 Operators - Domestic Trunk Airlines

| | CY | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 |
|----------------|----|------|------|------|------|------|------|------|------|------|------|------|
| <u>Airline</u> | | | | | | | | | | | | |
| American | | X | X | X | X | X | X | X | X | X | X | X |
| Braniff | | | | X | X | X | X | X | X | X | X | X |
| Continental | | | | X | X | | | | | | | |
| Delta | | | | | | | | | X | X | X | X |
| Eastern | | X | X | X | X | X | X | X | X | X | X | X |
| National | | X | X | X | X | X | X | X | X | X | X | X |
| Northwest | | X | X | X | X | X | X | X | X | X | X | X |
| Northwest | | X | X | X | X | X | X | X | X | X | X | X |
| TWA | | X | X | X | X | X | X | X | X | X | X | X |
| United | | X | X | X | X | X | X | X | X | X | X | X |

Table 3.4.1-II

B737 Operators - Domestic Local Service Airlines

| | CY | 1965 | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 |
|----------------|----|------|------|------|------|------|------|------|------|------|------|------|
| <u>Airline</u> | | | | | | | | | | | | |
| Frontier | | | | | | X | X | X | X | X | X | X |
| Piedmont | | | | | X | X | X | X | X | X | X | X |

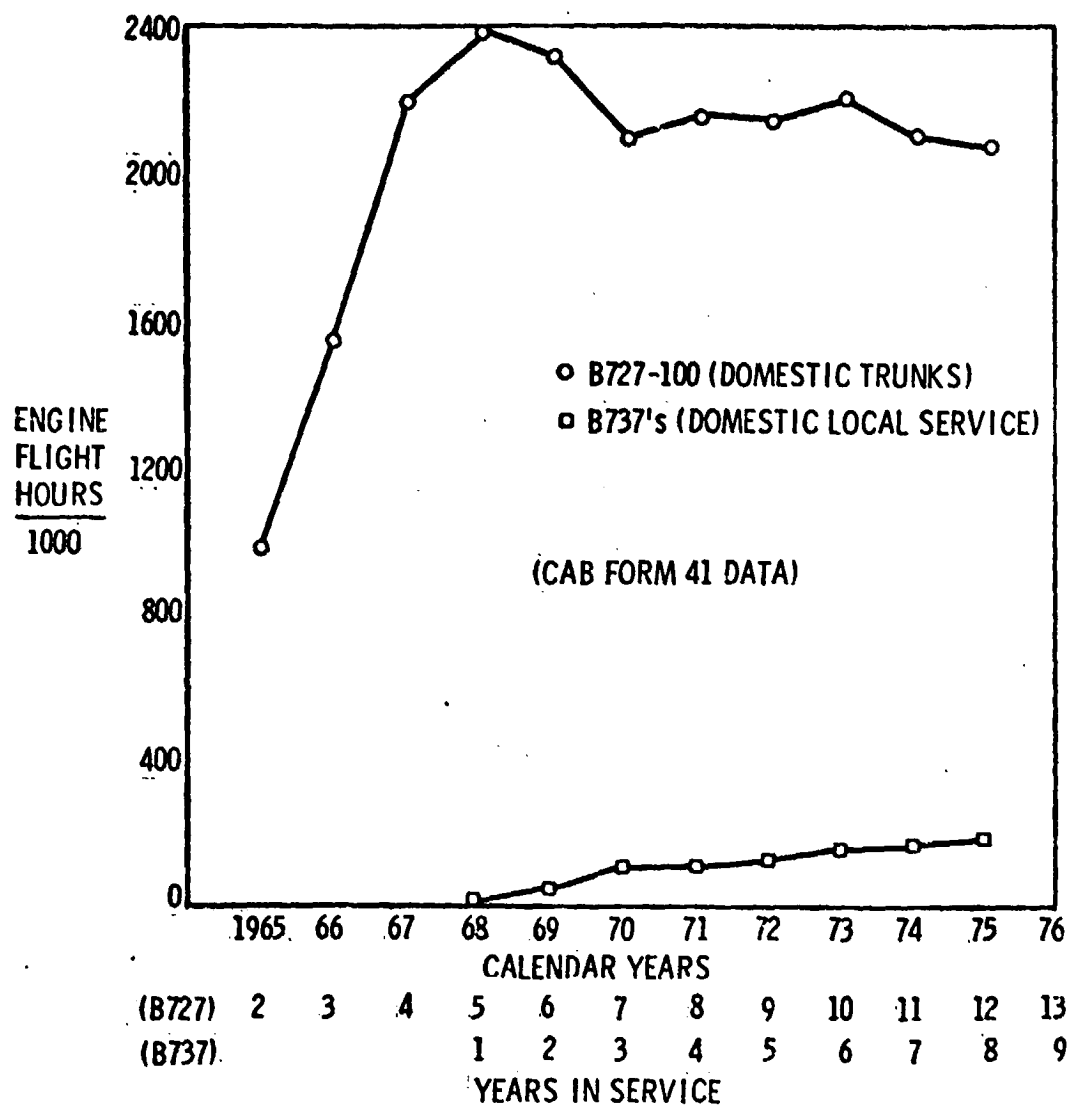


Figure 3.4.1-1. Engine flight hours - JT8D-1 & -7 engines.

Figure 3.4.1-2 shows the direct maintenance cost in dollars per engine flight hour plotted versus calendar years and years in service for the JT8D-1 and -7 engines for the two fleets of airlines. The costs have been adjusted for CY 1976 economy. The escalation factors shown in Table 3.3.1-III were used for the adjustment. A split of 40 percent for labor and 60 percent for material plus outside services was used to make the escalation adjustment for the different rates between labor and material shown in Table 3.3.1-III. The 40/60 split was determined from Eastern Airlines records for their JT8D operation in B727's and DC-8's. While the 40/60 split is indicative of trunk airlines, the effect of different splits for local service airlines was evaluated and was found to be minimal with respect to the effect in escalating costs.

Figure 3.4.1-2 shows the characteristic maturity (Reference 1) of the engine in the period from 8 to 11 years from its original introduction into service, which was in the B727. A direct maintenance cost of \$22.63 per engine flight hour was chosen for a mature JT8D when operated in the B727 with a duty cycle of .78 cycles per flight hour. The B737 was introduced into service four years later than the B727, but the engines show the same calendar year period of maturity as those in the B727. This is similar to the same characteristic shown for the 501-D13 turboprop engines for the Electra and CV580 airplanes. The engines in the B737 have benefited from the prior experience of those in the B727. A mature direct maintenance cost for the JT8D in B737 operation was selected at \$27.45 per engine flight hour.

The effect of duty cycle on engine reliability and maintenance cost was discussed in Section 3.3.1. For purposes of clarity in comparing the duty cycles of the 501-D13/54H60 turboprop system with those of the JT8D turbofan the following comparison is presented:

| | <u>Average Flight Time per Trip, Hrs.</u> | <u>Duty Cycles per Flight Hrs.</u> |
|---|---|--|
| JT8D/B727-100's Domestic Trunks | 1.28 | 0.78 |
| JT8D/B737's Domestic Local Service | 0.76 | 1.32 |
| 501-D13/Electra L188's Domestic Trunks | 0.80 | 1.25 |
| 501-D13/CV580's Domestic Local Service | 0.55 | 1.81 |

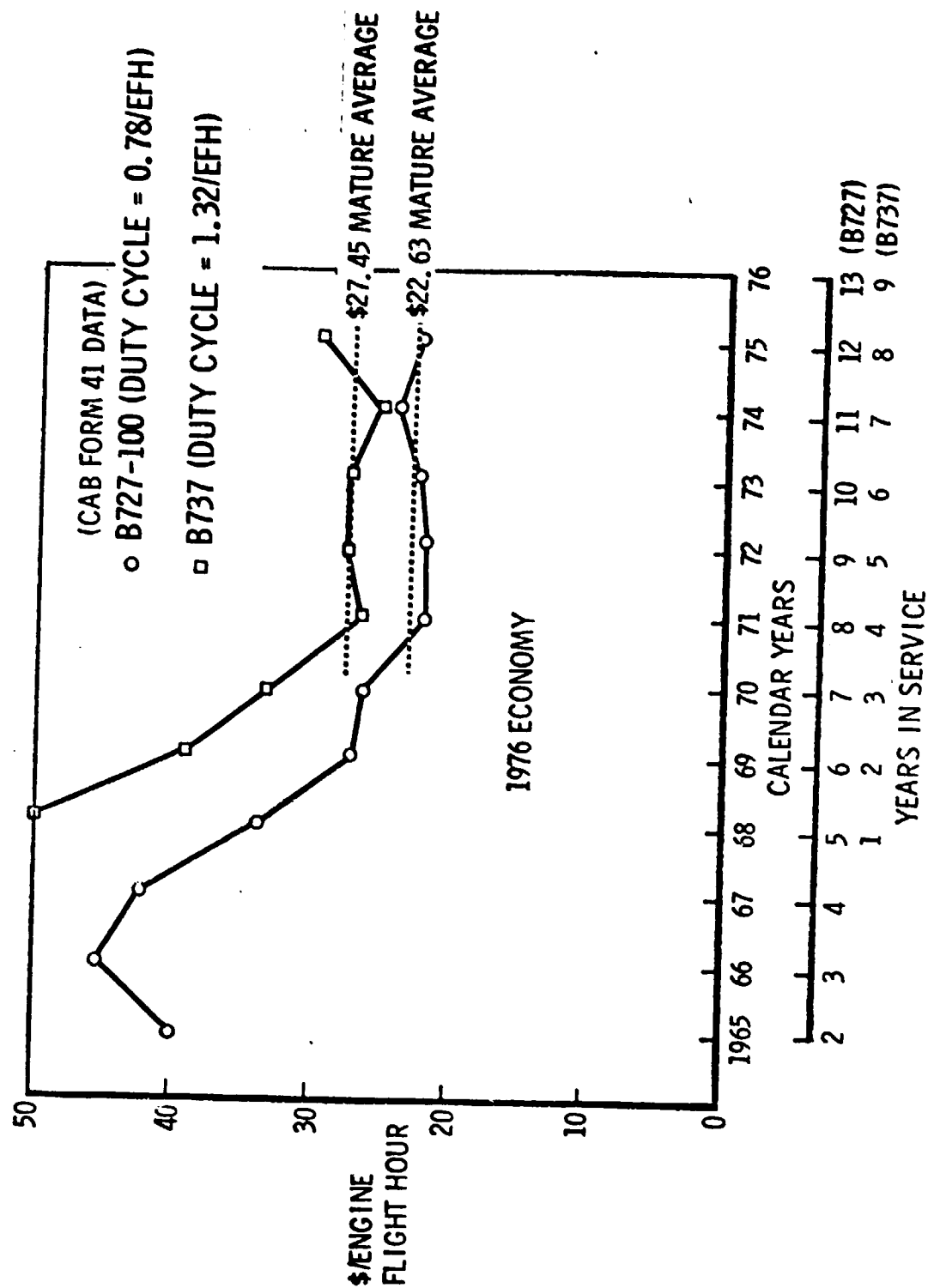


Figure 3.4.1-2. Direct cost per engine flight hour - JT8D-1 & -7 engines.

Fully burdened and unburdened mature engine costs per flight hour for the JT8D's were determined from the CAB Form 41 data by the same procedure used for the 501-D13's in Section 3.3.1. The results are shown in Table 3.4.1-II. These results show that when the direct costs are corrected to fully burdened and unburdened, which removes the inequality between the two fleets in the use of outside services, the newer engines in the fleet of B737's kept the engine maintenance cost level in that fleet lower than in the B727 fleet.

Table 3.4.1-II
JT8D Mature Direct, Burdened, and Unburdened Cost
per Flight Hour in B727-100's and B737's

| | \$ / Engine Flight Hour 1976 Economy | | |
|---|---|-----------------|-------------------|
| | <u>Direct</u> | <u>Burdened</u> | <u>Unburdened</u> |
| JT8D/B727-100 (Dom. Trunks) (Duty Cycle = 0.78/EFH) | 22.63 | 33.72 | 19.91 |
| JT8D/B737 (Dom. Local Serv.) (Duty Cycle = 1.32/EFH) | 27.45 | 30.47 | 18.39 |

3.4.2 Maintenance Cost of Turboprop System Scaled to JT8D Thrust Size

3.4.2.1 Engine and Reduction Gearbox

To draw a comparison between the turboprop system and the JT8D turbofan the systems must be put on a basis where they have equal capability to do the same job. Therefore, since DDA and Hamilton Standard were intimately familiar with the turboprop system, the best approach was to scale the turboprop system up to where it produced the same climb thrust as the JT8D-7 at 0.8M, 35,000 feet altitude. In this process it had to be assumed that a propeller that was equal in complexity, mechanical technology, and reliability as the Hamilton Standard 54H60 could be 80 percent efficient at .8M, 35,000 feet altitude. Similarly the engine would have the same cycle characteristics, mechanical technology, and reliability as the 501-D13. Under these conditions the 501-D13 engine was scaled to the equivalent of 12,226 shaft horsepower at SLS, compared to 3430 SHP in unity size. Compared to the unity size 501-D13 it was found that the engine and gearbox had to be scaled by the following factors:

| <u>Item</u> | <u>Factor</u> |
|------------------------------------|---------------|
| Engine Horsepower | 3.56 |
| Engine Diameter | 1.88 |
| Engine Length | 1.66 |
| Engine Weight | 3.55 |
| Reduction Gearbox Diameter | 1.16 |
| Reduction Gearbox Axial Length | 1.01 |
| Reduction Gearbox Weight | 1.32 |
| Torquemeter Length | 1.00 |
| Engine Acquisition Cost | 2.14 |
| Reduction Gearbox Acquisition Cost | 1.32 |

Using labor and material costs for the unity size 501-D13 engine and gearbox as a basis, new labor and material rates were estimated for the scaled up 501-D13. These estimates were based upon known experience with other DDA engines of increased size, weight, and acquisition cost. Frontier Airlines CV580 operation in CY 1975 was used for input to the DDA logistics cost model (Reference 9) where overhaul and repair removal rates were correlated with repair and overhaul costs to establish a baseline maintenance cost per flight hour of the 501-D13 that was equivalent to the Frontier reported cost in CAB Form 41 for CY1975. The same removal rates used in establishing the baseline maintenance cost were used in determining the maintenance costs of the scaled up 501-D13. Since duty cycle affects only the removal rates, a scale factor based upon equal duty cycles could determine the effects of the increased size of the system. Therefore the estimated labor and material rates for the scaled up 501-D13 were applied to the baseline removal rates to establish scaled up maintenance costs from which scaling factors could be determined for application to the mature maintenance costs of the 501-D13. The results that were obtained from the model analysis were as follows:

to the mature maintenance costs of the 501-D13. The results that were obtained from the model analysis were as follows:

| <u>Cost/Engine Flight Hour</u> | | |
|--------------------------------|---------------|-----------------------|
| <u>Basic 501-D13</u> | <u>Direct</u> | <u>Fully Burdened</u> |
| Engine & Installation | \$27.33 | \$39.88 |
| Reduction Gearbox | <u>3.04</u> | <u>5.40</u> |
| Total | \$30.37 | \$45.28 |
| <u>Scaled 501-D13</u> | | |
| Engine & Installation | \$38.69 | \$51.21 |
| Reduction Gearbox | <u>3.65</u> | <u>6.02</u> |
| Total | \$42.34 | \$57.23 |

Thus the scaling factors for the maintenance cost of a 501-D13 engine and gearbox, when scaled to 12,226 SHP, SLS rating, and keeping reliability rates and duty cycle constant, were as follows:

Scaling Factors for Direct Costs

$$\begin{aligned}\text{Engine \& Installation} &= 38.69 \div 27.33 = 1.416 \\ \text{Reduction Gearbox} &= 3.65 \div 3.04 = 1.201\end{aligned}$$

Scaling Factors for Fully Burdened Costs

$$\begin{aligned}\text{Engine \& Installation} &= 51.21 \div 39.88 = 1.284 \\ \text{Reduction Gearbox} &= 6.02 \div 5.40 = 1.115\end{aligned}$$

These scaling factors for size, and based upon the same duty cycle (no change in removal rates) were applied to the mature 501-D13 engine and gearbox maintenance costs shown in Figure 3.3.3-1 for Electra operations of 1.25 duty cycles per flight hour. The results were as follows:

Direct Maintenance Costs per Engine FLight Hour

$$\begin{aligned}\text{Engine \& Installation} &= \$20.72 \times 1.416 = \$29.34 \\ \text{Reduction Gearbox} &= \$2.28 \times 1.201 = \$ 2.74 \\ \text{Total} &= \$32.08\end{aligned}$$

Fully Burdened Maintenance Costs per Engine Flight Hour

$$\begin{aligned}\text{Engine \& Installation} &= \$35.23 \times 1.284 = \$45.24 \\ \text{Reduction Gearbox} &= \$ 3.87 \times 1.115 = 4.32 \\ \text{Total} &= \$49.56\end{aligned}$$

3.4.2.2 Propeller

Hamilton Standard has developed a parametric relationship of labor and material maintenance cost as a function of propeller size based on analysis of limited propeller data for two different propeller sizes. This relationship indicates that both labor expressed in manhours per repair and material expressed in parts cost per repair were approximately linear with changes to propeller diameter, if all other variables such as propeller complexity and technology level were constant.

The size of an 80% efficient four-blade propeller of JT8D thrust for 0.8M climb at 35,000 ft. altitude was calculated to be 15.2 ft. Thus maintenance costs of a propeller of 54H60 complexity and technology level was estimated by multiplying actual costs times the ratio of 15.2 to 13.5 (diameter of a 54H60 propeller) or 1.13.

Comparison of a scaled 54H60 with a JT8D turbofan required adjustment for changes in reliability as well as maintenance cost as a result of difference in duty cycle.

Examination of propeller reliability revealed that inherent reliability was not affected by duty cycle as commercial propeller hardware is designed for infinite life. However, non-inherent failures due to erosion and FOD of blades and heaters were directly proportional to exposure to such conditions, and were adjusted by the ratio of hours per flight. This was done for the HS 54H60 propeller based on Saturn L-382 data (Reference discussion in section 3.3.2.). The mature maintenance costs of the HS 54H60 propellers scaled to a JT8D thrust level and B737 duty cycle were as follows:

Maintenance Cost per Propeller Flight Hour

| | |
|----------------|--------|
| Direct | \$3.38 |
| Fully Burdened | \$3.62 |

3.4.2.3 Total Maintenance Cost of Turboprop System

To compare the mature maintenance costs of the scaled up 501-D13/54H60 turboprop system, the costs of the scaled 501-D13 engine and reduction gearbox did not have to be adjusted for duty cycle because the mature costs, based upon an Electra duty cycle of 1.25 per flight hour, would be approximately the same for the duty cycle of 1.32 per flight hour for the B737's.

The total maintenance cost of the 501-D13/54H60 mature turboprop system, scaled to give equivalent thrust at .8M, 35,000 feet altitude to the JT8D-7, and operating to the same duty cycle as the JT8D were as follows:

| | <u>Cost per FLight Hour</u> | |
|-----------------------|-----------------------------|-----------------------|
| | <u>Direct</u> | <u>Fully Burdened</u> |
| Engine & Installation | \$29.34 | \$45.24 |
| Reduction Gearbox | 2.74 | 4.32 |
| Propeller | <u>3.38</u> | <u>3.62</u> |
| Total | \$35.46 | \$53.18 |

3.4.3 Comparative Maintenance Costs of 501-D13/54H60 and JT8D

A comparison of the turboprop system with the JT8D is shown in Figure 3.4.3-1. The two left bars show the mature direct and fully burdened maintenance cost of the 501-D13/54H60 turboprop propulsion system scaled to give equivalent thrust to a JT8D-7 at .8M @ 35,000 feet altitude. The two right bars show the mature direct and fully burdened maintenance costs of the JT8D when operated in the B737. For the JT8D an estimate of the fan and LP turbine cost was made based upon data from Reference's 1 and 2. From these reports it was estimated that the fan maintenance costs were approximately the following percentages of the total:

| | |
|----------------|-------|
| Labor | 6.0% |
| Material & OSS | 3.66% |

From Reference 1 it was estimated that the thrust reverser maintenance cost was approximately 6% of the total JT8D maintenance cost per flight hour. Using these estimations the fan portion of the total \$27.45 mature direct maintenance cost was \$1.26, and the reverser portion was \$1.65. The remainder of \$24.54 accounts for the core and all other installation costs included in ATA chapters 71 through 80. Similarly the fully burdened cost for the fan was \$1.53 and for the reverser was \$1.83, and the remainder was \$27.11.

The comparison in Figure 3.4.3-1 shows that the fully burdened cost per flight hour of the propeller and gearbox vs. the fan and reverser of the JT8D is on the order of 8 to 3. The core and installation costs of the turboprop are also higher than that of the turbofan by a factor of approximately 2 to 1. The turboprop core costs represent older technology and older maintenance practices than the turbofan core costs. Based upon equivalent technology the maintenance cost of a basic turboprop engine core (compressor, combustor, turbine, accessory gearbox) will be less than that of the equivalent core of the turbofan engine, because it is physically smaller for an equivalent total system thrust. The comparison indicates that appreciable improvements must be made in the

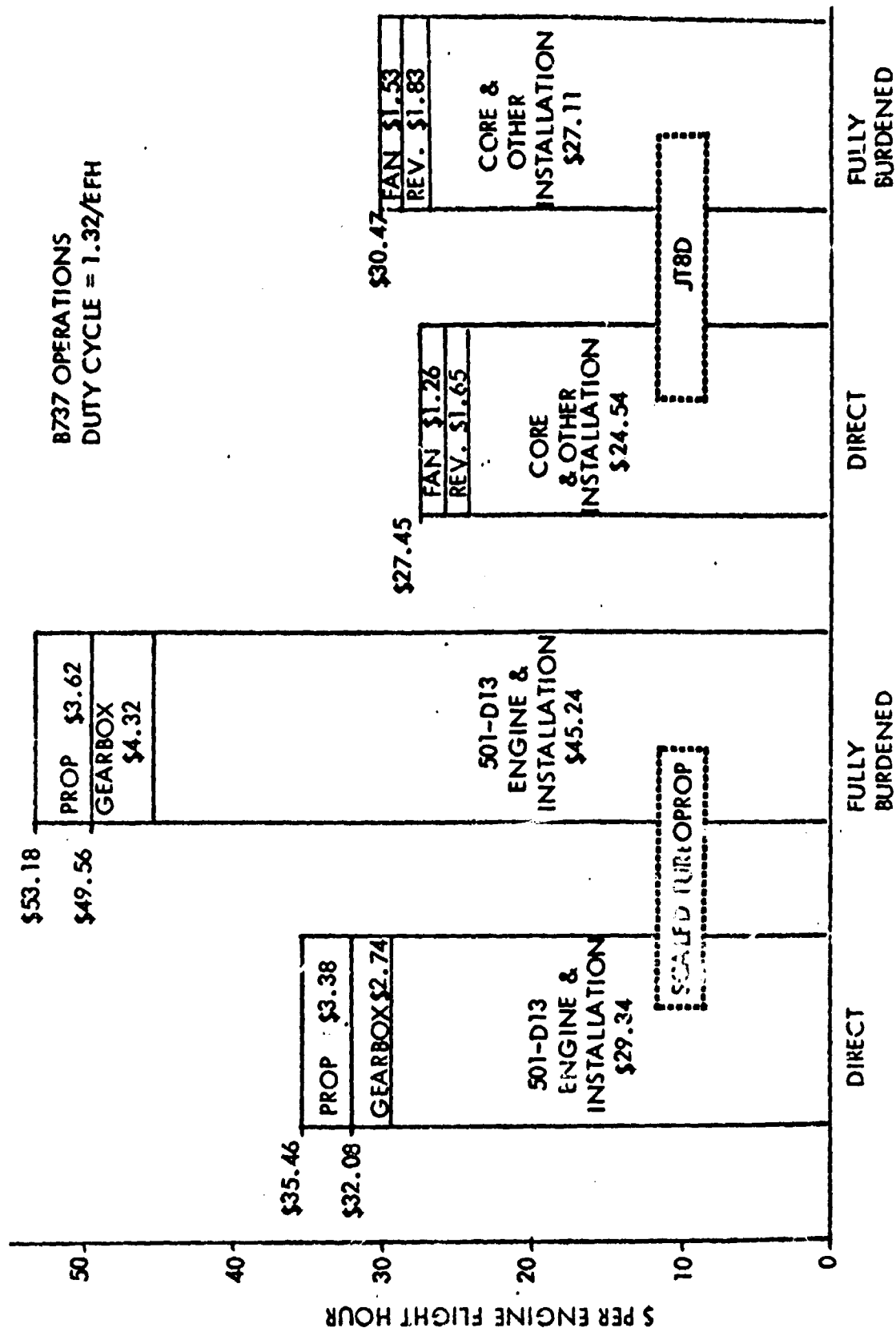


Figure 3.4.3-1. Comparison of turboprop and JT8D maintenance costs per engine flight hour.

propeller and reduction gearbox maintenance costs to offset those of the fan and thrust reverser in the turbofan installation and to make the two systems reasonably competitive from a maintenance cost standpoint.

3.4.4 High Bypass Turbofan Maintenance Costs

Figure 3.4.4-1 shows direct maintenance costs for JT9D's, F6-6's, and RB211's. The costs have been expressed in 1976 economy which were adjusted in a similar manner as for the JT8D engine. In the case of the high bypass ratio engines, a split of 20% labor and 80% material was used for application of the escalation factors. It is clear from Figure 3.4.4-1 that no indication of a mature engine maintenance cost is yet evident and therefore no comparisons were made to the turbo-prop system.

Figure 3.4.4.-2 shows a comparison of the mature direct JT8D maintenance cost from Figure 3.4.3-1 with that of the JT9D from Figure 3.4.4.-1. This comparison implies equal cost on \$/lb thrust basis but there is a large difference in cyclic usage. If the high bypass ratio engine (JT9D) were operated at the same cycle as the JT8D, its costs would be at a higher level. It is not clear where the projected mature level will be for the high bypass engine with respect to the JT8D.

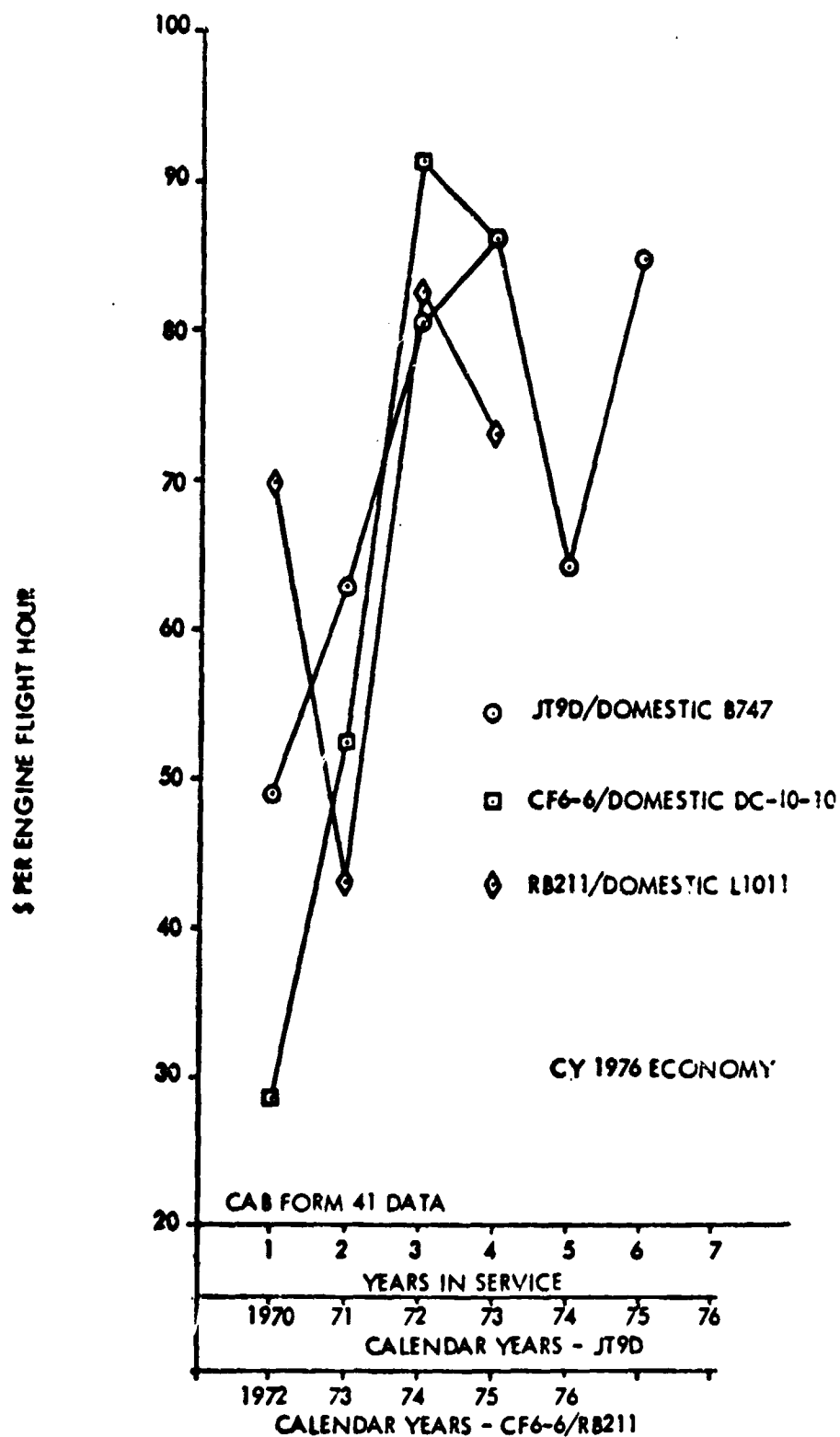


Figure 3.4.4-1. Direct maintenance cost per engine flight hour for JT9D, CF6-6, and RB 211 engines.

ENGINE RATINGS:
MAX. CLIMB, UNINSTALLED THRUST
AT 0.8M, 35,000 FT. ALTITUDE

CY 1976 ECONOMY

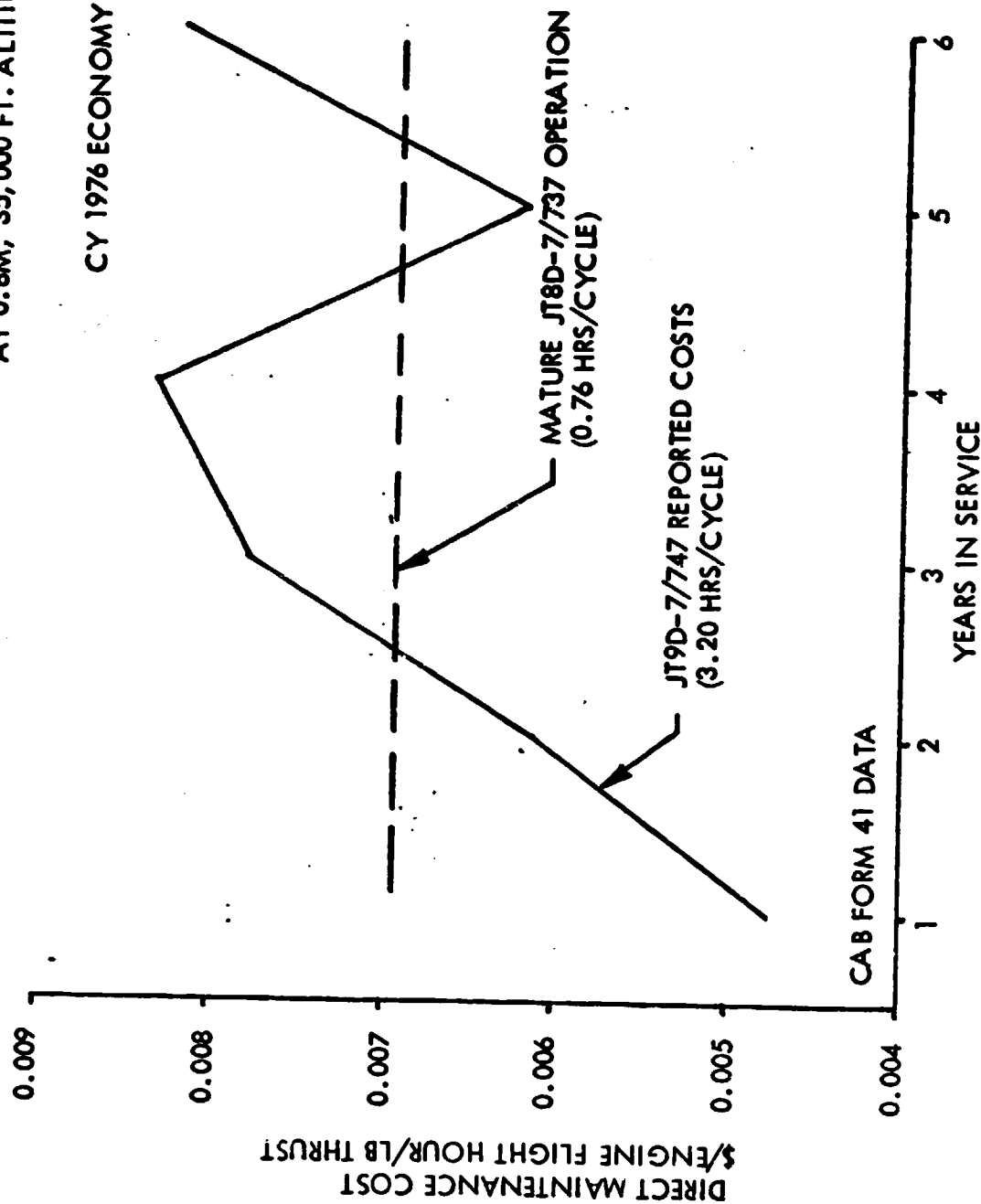


Figure 3.4.4-2. Comparison of JT8D-7 and JT9D-7 engine direct maintenance costs per pound thrust.

3.5 Reliability and Maintenance Cost Analysis

To conduct the reliability analysis and to detail the maintenance costs for purposes of determining the maintenance cost drivers, maintenance actions during the mature years of engine operation were analyzed.

3.5.1 Maintenance Cost Analysis

3.5.1.1 501-D13 Engine and Reduction Gearbox

The analysis in Section 3.3.1 shows the mature years of engine operation were from CY 1966 to 1969 (reference Figure 3.3.1-1). Figure 3.3.1-4 shows that during this period Electra operations were at a maximum in CY 1965 and 1966 while CV580 operations were nearing their maximum in CY 1967 and 1968. Therefore the maintenance actions for the Electra and CV580 were analyzed for these respective periods. Section 3.2.1 outlines the detailed type of data that was available for this time period in terms of removal rates and reasons therefor. Eastern Airlines overhaul and repair costs for CY 1967, reference Table 3.2.3.3.1-1, were used as a basis to determine the cost drivers in the engine and reduction gearbox. CY 1967 costs were escalated to CY 1976 economy by the escalation factors presented in Table 3.3.1-III. Time expired and premature removals of the engine and reduction gearbox for the CY 1965 to 1968 period discussed above were tabulated, with detailed reasons for the premature removals in Reference 3. The Eastern Airlines overhaul and repair costs were applied to the tabulated removal data with the following results:

Table 3.5.1.1-I
Shop Overhaul & Repair Costs of Representative Electra
and CV580 501-D13 Removals in CY 1965 to 1968
(1976 Economy)

| | <u>Number Removals</u> | <u>Cost per Removal</u> | <u>Total \$</u> | <u>\$/EFH*</u> | <u>%</u> |
|--------------------------------|----------------------------|-----------------------------|---------------------|----------------|----------|
| Overhaul (time expired) | | | | | |
| Compressor | 206 | \$44,477 | 9,162,222 | 3.68 | 21.3 |
| Turbine | 174 | 35,577 | 6,190,360 | 2.48 | 14.4 |
| Reduction Gear | 206 | 11,849 | 2,440,844 | 0.98 | 5.7 |
| Repair (premature removals) | 1444 | 17,420 | 25,153,866 | 10.09 | 58.6 |
| | | Total | 42,947,292 | \$17.23 | 100.0 |

*EFH = Engine flight hours = 2,492,467

Table 3.5.1.1-I contains shop costs only. The only element of cost lacking from this tabulation is line labor. From Eastern Airlines records, a sampling of data showed that over a period of two years Eastern's line labor varied from 9.09 to 11.87 percent of total maintenance cost. Assuming an average of 10.48 percent the total maintenance cost of the representative removals in Table 3.6.1.1-I would have been $\$17.23 \div 0.8952 = \19.25 . Since the removals listed in Table 3.5.1.1-I represent a mixture of Electra and CV580 operation from 1965 to 1968, reference to Figure 3.3.1-1 shows that the \$19.25/engine flight hour is representative of the reported mature direct maintenance costs of the 501-D13 engine and gearbox in both Electra and CV580 operation. A further analysis of the direct maintenance costs in the shop was made to determine the cost drivers.

The results shown in Table 3.5.1.1-I are shown in bar chart form in Figure 3.5.1.1-1, expressed as percentages of the total shop maintenance cost. The left bar shows that scheduled removals, or time expired removals, are a primary cost driver. They comprise 41.4% of the total shop maintenance costs. This shows the need for on-condition maintenance that is justified by higher reliability of equipment, improved on-line inspection techniques, and built-in automatic condition monitoring capability. The lower part of the middle box shows that the primary cost drivers within the time expired removals were the compressor and turbine. Replacement and repair of the blading in both components were the primary cost elements within these two components.

Repair costs for premature removals amounted to 58.6% of the total shop maintenance, as shown in the upper part of the left and middle bars of Figure 3.5.1.1-1. Since these removals were identified by the cause of the removal, the cost drivers within the premature removals were identified by major component as shown in the middle bar. Turbine failures were the highest cost driver, 20%. Within the turbine the following failures in order of magnitude were the primary cost drivers:

1. Blades, vanes, and spacers.
2. Bearings and supports

The next highest cost driver was non-inherent failures, 19.5%. Table 3.5.1.1-II shows the breakdown for the causes of non-inherent removals in order of descending cost:

Table 3.5.1.1-II
Non-Inherent Premature Removal Cost Percentages

| | |
|------------------------------------|-------------|
| Unsubstantiated (no failure found) | 5.1% |
| FOD | 3.7% |
| Improper Maintenance | 3.3% |
| Compressor Erosion | 2.5% |
| Modifications | 1.6% |
| Accidents | 1.6% |
| Overtemp Operation | 0.9% |
| Convenience | 0.5% |
| Others | 0.3% |
| | <hr/> 19.5% |

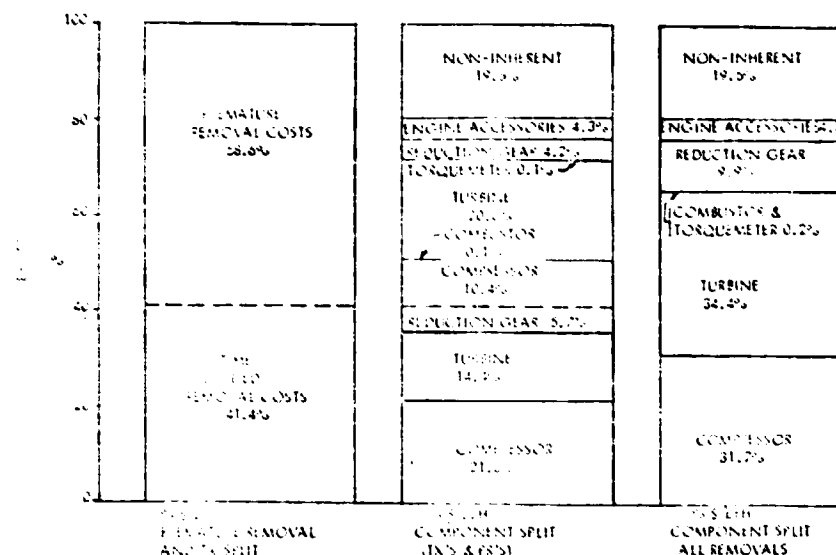


Figure 3.5.1.1-1 Breakdown of shop maintenance costs, 501-D13 engine and gearbox.

Unsubstantiated removals can be prevented with condition monitoring and improved inspection techniques. FOD and compressor erosion can be decreased through greater attention to inlet location and more rugged compressor blading. Improper maintenance can be reduced with better diagnostics (condition monitoring), clearer maintenance instructions, and less frequent removals.

Failures in the compressor accounted for 10.4% of all removal costs. The primary cost drivers, in order, were:

1. Rear compressor bearing failures.
2. Blade and vane failures.
3. Diffuser assembly.

Premature removals of engine accessories accounted for 4.3% of all shop maintenance costs. These components were primarily in the control and fuel system, and many times were the result of "fault elimination by trial" type of maintenance. A fully integrated digital electronic control with built-in diagnostics would reduce the frequency of these removals.

Premature removals of the reduction gearbox accounted for 4.2% of all shop maintenance cost. Of this, almost one-half was in the engine accessory and aircraft accessory drive systems. Extensive consideration was given in Task II to means of removing these accessory drives from the reduction gearbox where they can be modularized and removed easily without the necessity of the main drive reduction gearbox removal.

The right bar of Figure 3.5.1.1-1 shows the component contribution to total maintenance cost when scheduled and unscheduled removal costs are added together.

3.5.1.2 Hamilton Standard 54H60 Propeller

The propeller reliability data and cost data collected in this program was discussed in Section 3.3.2. This discussion established the mature propeller maintenance costs and the maintenance events relating thereto.

The developed maintenance cost for the HS 54H60 propeller has been summarized in a bar chart, Figure 3.5.1.2-1, to identify the cost drivers. From this chart it is clear that the dominant maintenance cost driver is scheduled maintenance requirements.

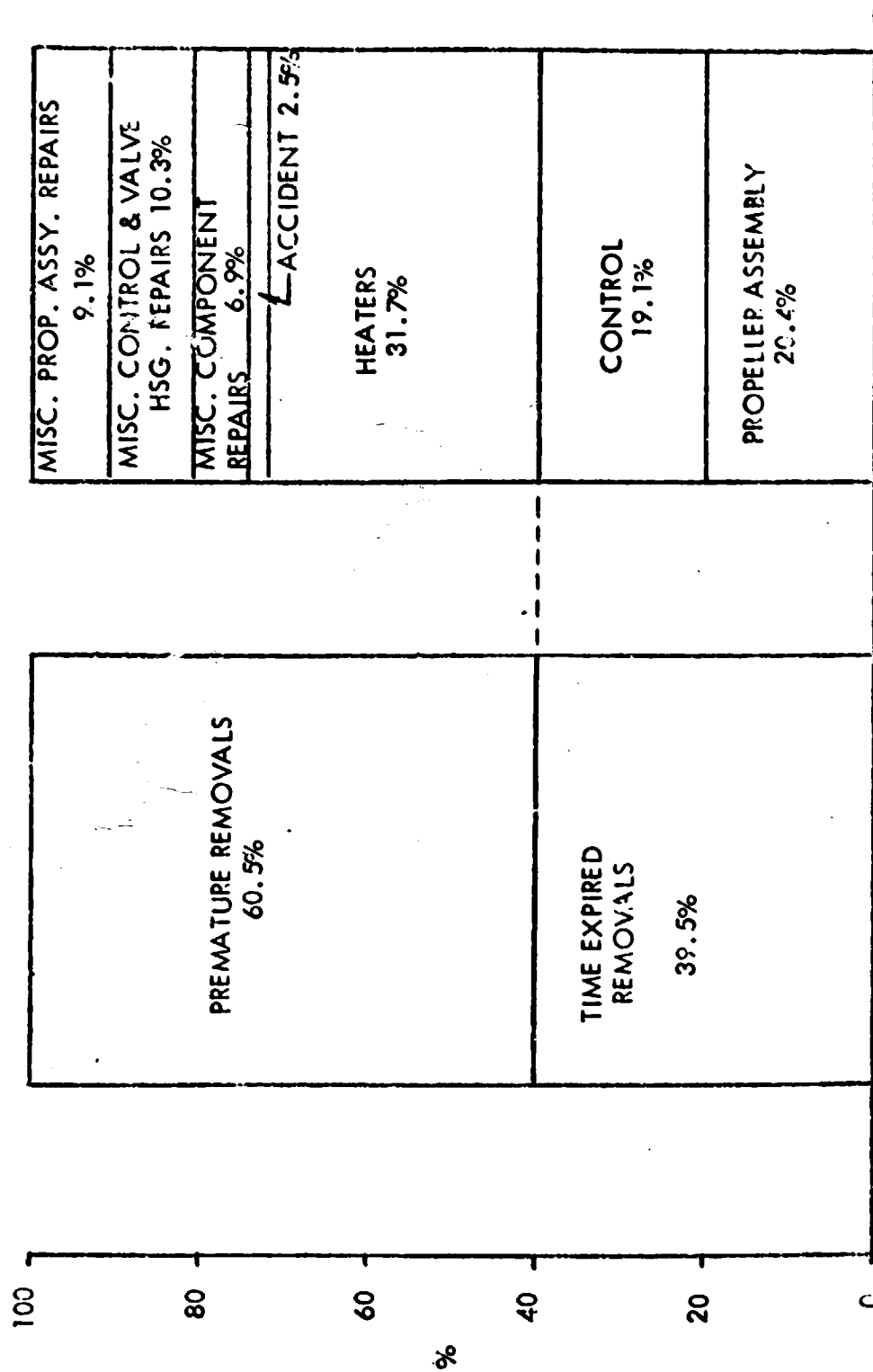


Figure 3.5.1.2-1 Breakdown of shop maintenance costs, 54H60 propeller .

Blade heaters are the second significant cost driver. Control and propeller assembly repair costs rank third and fourth, respectively.

3.5.1.3 Costs Characteristic to Turboprop Functions

The percentages shown in Figures 3.5.1.1-1 and 3.5.1.2-1 for the engine, gearbox, and propeller can be used to show the maintenance cost of turboprop versus non-turboprop functions within the turboprop system. Functions which can be considered as non-turboprop are:

- Power Section
- Engine Accessory Drive
- Aircraft Accessory Drive

The propeller and the main drive system of the reduction gear would be considered as turboprop functions.

Referring to Figure 3.4.3-1, the reduction gear and engine fully burdened mature maintenance cost is \$49.56 for the 501-D13 scaled to the thrust size of the JT8D. Of this total the reduction gear was \$4.32. The reduction gearbox maintenance cost was broken down into the three functions: the main drive system, engine accessory drive, and aircraft accessory drive as follows:

| | <u>%</u> | <u>\$/EFH</u> |
|--------------------------|-------------|---------------|
| Main Drive System | 56.7 | 2.45 |
| Engine Accessory Drive | 16.7 | 0.72 |
| Aircraft Accessory Drive | <u>26.6</u> | <u>1.15</u> |
| | 100.0 | 4.32 |

Thus only \$2.45 of the total reduction gear cost is chargeable to turboprop related functions. A comparison of the turboprop system with the JT8D turbofan would then be as shown in Figure 3.5.1.3-1. The non-turboprop related functions are directly related to the core and installation functions of the turbofan system.

3.5.2 Reliability Analysis

Airline operation of turboprop aircraft during prior years were studied to provide baseline data. Electra L-188 reliability data of the 1965-66 time period and Convair 580 data of the 1967-68 time period were examined to:

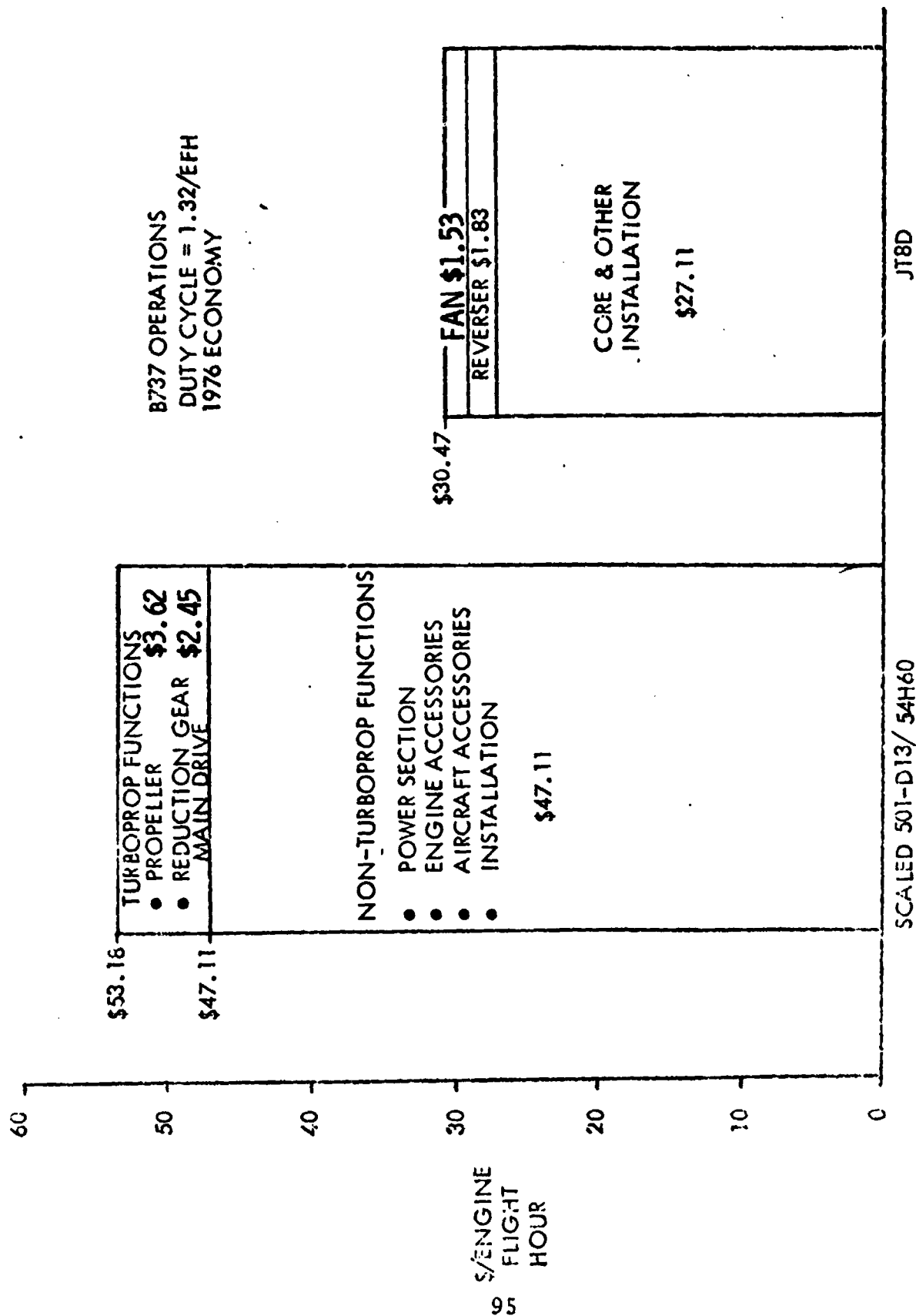


Figure 3.5.1.3-1. Turboprop and non-turboprop functions compared to JT8D maintenance costs.

- Better understand the relative reliability of the propulsion subsystems of the 1965-68 era.
- Establish a base for comparison with projected 1990 reliability of propulsion subsystems.
- Assist in defining maintenance plans and design criteria for a projected 1990 era propulsion system.

The combined L-188 and CV580 historical data were divided into several sets of groupings. One such grouping divided the data into:

- Events which were primarily propulsion system equipment caused--termed "inherent"
- Events which were primarily not caused by propulsion system--termed "non-inherent."

The historical data were also divided into another set of two primary groupings:

- Premature removal causes related to hardware which would be required regardless of the propulsion type, i.e., turbo-prop, turbofan or turboshaft.
- Premature removal causes related to propulsion hardware unique to turboprops.

The first group was subdivided into premature removals of the core engine, the engine accessory drive train of the gearbox, and the aircraft accessory drive train of the gearbox. These subdivisions of historical data relate to some of the modular concepts studied to ensure a favorable maintenance plan. These are shown in Table 3.5.2-I.

The second group was subdivided into premature removals of the propeller and the power train reduction portion of the gearbox. These are shown in Table 3.5.2-II.

The inherent events are listed first in Tables 3.5.2-I and II, the non-inherent events next, and last the summary and premature removal rate calculations.

Table 3.5.2-I
CY 1965-68 Turboprop Propulsion System
Premature Removals Not Unique to Turboprop Power*

| Items Charged with Cause of Engine or Major Module Removal | Number of Engine or Major Module Removals |
|---|---|
| Compressor Section (Inherent) | 171(C) |
| Combustion Section (Inherent) | 11 (C) |
| Turbine Section (Inherent) | 189(C) |
| Accessories (Inherent) | 17 |
| Power Section Not Specifically Identified by Part (Inherent) | 50 (C) |
| Gearbox (Engine Functions) (Inherent)** | |
| Starter Shaft Bearings | 30 |
| Starter Drive Shaft | 26 |
| Starter Gear Nut Lock Washer | 8 |
| Starter Shaft Bearing Flange Bolt | 4 |
| Starter Shaft Seal | 3 |
| Starter Gear | 3 |
| Starter Drive Bearing Flange | 1 |
| Main Oil Pressure Pump | 4 |
| Oil Drain Plug Insert | 1 |
| Apportionment of "Failure Unknown" | 11 |
| Subtotal | 91 |

* Source: L-188 Electra non unit exchange engine data during 1965-66 and CV580 engine data during 1967-68 published in Reference 3.

** Probable Cause Related to Drive of Engine Accessories

+ Probable Cause Related to Drive of Aircraft Accessories

(C) Related to the core engine

Table 3.5.2-I (Cont'd)
CY 1965-68 Turboprop Propulsion System

| Items Charged with Cause of Engine or Major Module Removal | Number of Engine or Major Module Removals |
|---|---|
| Gearbox(Aircraft Accessory Drive Related) (Inherent)+ | |
| Alternator Drive Shaft | 35 |
| Alternator Drive Gear | 7 |
| Alternator Drive Shaft Bearing | 1 |
| Alternator Drive Shaft Tablock Washer | 1 |
| Alternator Drive Shaft Plug | 1 |
| Hydraulic Pump Idler Drive Gear | 14 |
| Hydraulic Pump Drive Gear | 8 |
| Hydraulic Pump Idler Gear Bearing | 5 |
| Hydraulic Pump Drive Shaft | 5 |
| Hydraulic Pump Drive Shaft Bearing | 3 |
| Hydraulic Pump Idler Gear | 3 |
| Hydraulic Spanner Nut Washer | 1 |
| Main Idler Gear Bearing | 2 |
| Main Accessory Drive Idler Gear | 3 |
| Accessory Drive Gear Bolt | 1 |
| Tach Drive Shaft Bearing | 7 |
| Tach and Oil Pump Drive Gear | 2 |
| Tach Drive Tablock Washer | 2 |
| Tach Idler Gear Bearing | 1 |
| Tach Drive Shaft | 1 |
| Oil Pump Drive Shaft Bearing | 3 |
| Oil Pump Drive Bushing Pin | 1 |
| Oil Pump Drive Idler Bearing | 2 |
| Apportionment of "Failure Unknown" | 15 |
| <hr/> | |
| Subtotal | 124 |
| Total (Inherent) | 653 |
| Engine (Non-inherent) | |
| Convenience | 316 |
| Unsubstantiated (No Failure Found) | 97 |
| Improper Maintenance | 63 |
| FOD | 44 |
| Compressor Erosion | 28 |
| QEC Failure(Secondary Damage to Eng) | 27 |
| Accident | 19 |
| Modifications | 28 |
| Overtemperature Operation | 12 |
| Oil Contamination | 4 |
| Cockpit Procedure | 2 |
| <hr/> | |
| Total (Non-inherent) | 641(C) |

Table 3.5.2-I (Cont'd)
CY 1965-68 Turboprop Propulsion System

| <u>Items Charged with Cause of Engine or Major Module Removal</u> | <u>Number of Engine or Major Module Removals</u> |
|--|--|
| Summary and Calculations: | |
| Total Engine Flight Hours | 2,492,467 |
| Inherent Premature Removals: | |
| Total Number | 653 |
| Rate per 1000 Eng. Flt. Hours | 0.262 |
| Non-inherent Premature Removals | |
| Total Number | 641 |
| Rate per 1000 Eng. Flt. Hours | 0.257 |
| Total Premature Removals - - All Causes | |
| Total Number | 1,294 |
| Rate per 1000 Eng. Flt. Hours | 0.519 |
| Total Premature Removals of the Core Engine Portion - - All Causes | |
| Total Number | 1,062 |
| Rate per 1000 Eng. Flt. Hours | 0.426 |
| Total Premature Removals Not Unique to the Core Engine---All Causes | |
| Total Number | 234 |
| Rate per 1000 Eng. Flt. Hours | 0.094 |

Table 3.5.2-II
CY 1965-68 Turboprop Propulsion System
Premature Removals Unique to Turboprop Power*

| Items Charged with Cause of Engine or Major Module Removal | Number of Engine or Major Module Removals |
|---|---|
| Propeller (Inherent) | 1376** |
| Propeller (Non-inherent) | 339** |
| Gearbox (Turboprop Functions) (Inherent) | |
| Planet Gear and Bearing Assy | 26 |
| Planet Rear Carrier Bearing | 3 |
| Rear Carrier Bearing Retaining Plate | 2 |
| Rear Pinion Bearing | 11 |
| Front Pinion Bearing | 9 |
| Pinion Shaft Gear Bushing | 9 |
| Pinion Gear | 1 |
| Pinion Gear Key Washer | 1 |
| Pinion Bearing Nut Lock Pin | 1 |
| Prop Brake Assy | 5 |
| Ring Gear Bolt | 1 |
| Prop Brake Seal | 2 |
| Main Drive Gear | 4 |
| Main Drive Gear Bearing | 1 |
| NTS Indicator Plunger | 3 |
| NTS Actuator Seal | 1 |
| NTS Spline Ring | 1 |
| Sun Gear Tablock Washer | 2 |
| Prop Shaft Bearing Seal | 2 |
| Prop Shaft Thrust Bearing | 1 |
| Prop Shaft Belleville Washer | 1 |
| Inner Rear Case Diaphragm | 3 |
| Rear Case | 2 |
| Main Diaphragm | 2 |
| Swivel Upper Mount Arm | 5 |
| Internal Retaining Ring | 3 |
| Split External Retaining Ring | 1 |
| Delivery Flange Bushing | 2 |
| Apportionment of "Failures Unknown" | 15 |
| Subtotal | 120 |

*Note 1: Source was L-188 Electra non unit exchange engine data during 1965-66 and CV580 engine data during 1967-68 published in Reference 3.

**Note 2: Based on the flight hours of the 1965-68 base period and the premature removal rates from the propeller data base period per Section 3.2.3.2.2 as adjusted to the Electra duty cycle of 1.25/EFH.

Table 3.5.2-II (Cont'd.)
CY 1965-68 Turboprop Propulsion System
Premature Removals Unique to Turboprop Power*

| <u>Items Charged with Cause of Engine or Major Module Removal</u> | <u>Number of Engine or Major Module Removals</u> |
|---|--|
| Torquemeter (Inherent) | 30 |
| Torquemeter (Non-inherent) | 0 |
| Summary and Calculations | |
| Total Engine Flight Hours | 2,492,467 |
| Inherent Premature Removals | |
| Total number | 1,526 |
| Rate per 1000 Eng. Flt. Hours | 0.612 |
| Non-inherent Premature Removals | |
| Total Number | 339 |
| Rate per 1000 Eng. Flt. Hours | 0.136 |
| Total Premature Removals -- All Causes | |
| Total Number | 1,865 |
| Rate per 1000 Eng. Flt. Hours | 0.748 |

The contribution of each propulsion system major module to the total premature removal rate of the major modules is shown in Table 3.5.2-III and graphically in Figure 3.5.2-1.

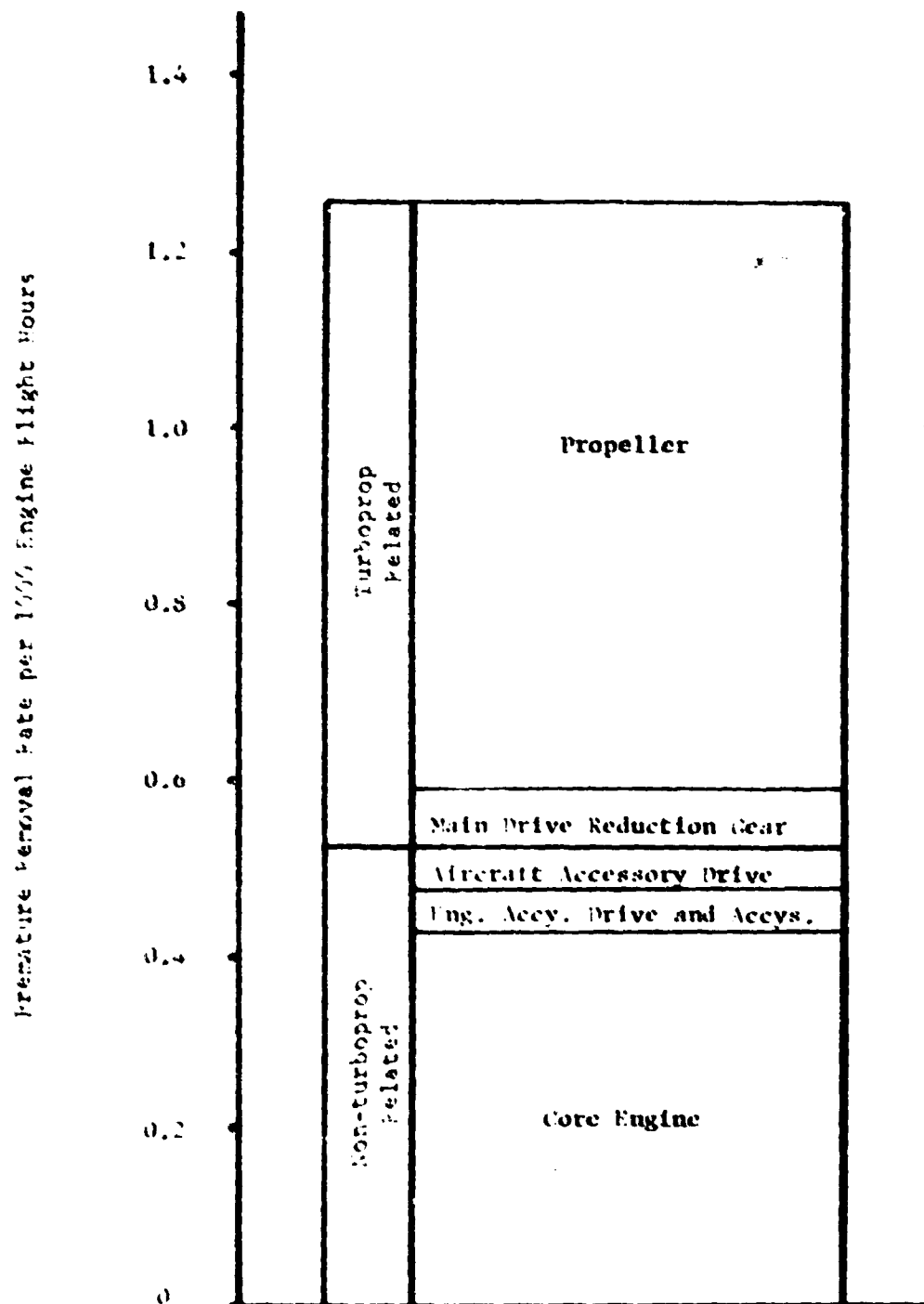


Figure 3.5.2-1. Contribution of each major module to the total major module premature removal rate during CY 1965 - 1968

Table 3.5.2-III
Contribution of Each Major Module to the Total Major
Module Premature Removal Rate During CY 1965-68*

| | <u>Number of Premature Removals-All Causes</u> | <u>Premature Removal Rate Per 1000 Hours</u> |
|--------------------------------|--|--|
| <u>Non Turboprop Related</u> | | |
| Core Engine | 1062 | 0.426 |
| Engine Accy Drive & Accys** | 108 | 0.043 |
| A/C Accy Drive | 124 | 0.050 |
| <u>Turboprop Related</u> | | |
| Power Train Reduction | 150 | 0.060 |
| Propeller*** | 1667 | 0.688 |

* Engine flight hours = 2,492,467 during 1965-68

**Accessory failures which in turn caused failure of a major module

***See Table 3.5.2-II, Note 2.

The study of premature removals was of extreme interest because it provided an insight to the contribution of different portions of the propulsion system to the total major module premature removal rate. Each such removal generates a cost and a challenge to any future design to lessen the frequency as well as the impact of such a failure should it occur.

Additional engine and reduction gear reliability studies were made to supplement those previously discussed. These were performed to:

- Review recent reliability history of turboprop powered aircraft for comparison to the 1965-68 period data and to provide reliability information of components and accessories not available for the 1965-68 period.
- Assess the nature of the principle detail part problems which lead to major module removals during the 1965-68 period to provide information to be used in preparing the Design Requirements Document and in making the estimates of reliability for a 1990-era turboprop propulsion system.

Operational and propulsion reliability data of CV580 aircraft operated by Frontier Airlines during 1975 were studied. One objective was to compare major unit removal rates during 1975 with the rates recorded for the 1965-68 period. Some of the comparisons reflect changes in maintenance practices; others reflect the net effects of improvements introduced during or after the 1965-68 time period and the increasing failure rate due to the increased age from 1967-68 to 1975. Comparative premature removal rates are shown in Table 3.5.2-IV.

Table 3.5.2-IV
Comparative Premature Removal Rates
CY 1965-68 and 1975

| <u>Major Module</u> | <u>Premature Removals Per 1000 Engine Flight Hrs.</u> | | <u>Remarks</u> |
|----------------------------|---|----------------|----------------|
| | <u>CY 1965-68</u> | <u>CY 1975</u> | |
| Engine & Turbine Unit Only | 0.426 | 0.592 | Note 1 |
| Reduction Gearbox | 0.154 | 0.031 | Note 2 |

Note 1. The increase from CY 1965-68 to CY 1975 probably reflects the age effect.

Note 2. Maintenance practice changes in CY 1975 from CY 1965-68 included repairing accessory drive problems on the wing when possible.

The group of removals which generates almost 50% of the maintenance costs are the Time Expiration Removals resulting from operating with a stipulated, limiting Time Between Overhaul (TBO) or a maximum operating time between mandatory complete overhauls. During the 1965-68 period of study there were 206 scheduled engine, 174 scheduled turbine and 568 scheduled propeller (as determined per Note 2 of Table 3.5.2-II) major module removals for time expiration. These totaled 948 and a rate of 0.380 per 1000 engine and propeller flight hours. Although the rate is less, the maintenance cost associated with each time expiration removal is considerably more than an average premature removal as discussed in Sections 3.5.1.1 and 3.5.1.2. Scheduled maintenance including overhauls has been the historical maintenance philosophy for propeller systems. There has been no attempt to update the maintenance philosophy to reflect the current concept for turbofan propulsors of On-Condition maintenance whereby scheduled overhauls and inspections are eliminated. However, the On-Condition concept is now considered viable for propellers and has been recommended for new propeller systems such as used on the DHC-7 aircraft (1977IOC). The concept of on-condition maintenance must be implemented to control this aspect of maintenance costs.

The data relating to the premature removal portion of the cost drivers were studied as to the general cause of failures. The purpose of the study was to determine if the causes of the part failures within the major modules could be controlled by current day technology or the technology likely available for a 1990 turboprop. The conclusions by major module were:

- Core Engine

The principle problems of the compressor and turbine were ones amenable to improved design approaches. Many problems were resolved in later models of the 501. Also there were no problems identified as being unique to turboprop power. There is no reason to believe that a turboprop core engine should be any less reliable than a turbofan core engine of the same era and same system thrust ratings.

- Engine and Aircraft Accessory Drives

The principle problems observed in these two systems were related to marginal designs for the high operating times of commercial engines and the more severe than anticipated loadings of the accessories. Improved life specifications and knowledge of accessory imposed loads would help considerably in any new design. These approaches are being used currently for other engines and can be expected to further improve for a 1990 era propulsion system. The review of the data indicated that during 1965-68 failures within these accessory drive trains resulted in the removal of the entire gearbox (as well as the propeller). Today airlines are doing much of the accessory drive preventive maintenance and repair on the wing to avoid the cost of removing the unit. This was considered as further evidence of the need to achieve greater modularity so that the system can be restored quickly with minimum hardware change.

- Main Drive Reduction Gear System

This system is unique to turboprop propulsion. Therefore, its reliability potential is important to the future of turboprop propulsion. During the 1965-68 period this portion of the 501-D13 reduction gearbox had a premature removal rate of 0.060/1000 hrs. or an equivalent MTBR of 16,700 hours. During 1975, the net effect of design and maintenance improvements, offset by an increment for high age, was that the observed removal rate was no more than 0.031/1000 hours or an equivalent MTBR of over 32,200 hours. Improvements in bearing design available today can be expected to result in reduction gear systems for the 1990 era of higher reliability.

- Propeller

In the case of the 54H60 propeller, blade heater failures is the second significant cost driver after scheduled overhauls. Control and propeller assembly repair costs rank next in importance. Heater failures necessitate removal of the propeller assembly to effect repair. The heater failures are due primarily to their vulnerability to environmental damage such as Foreign Object Damage (FOD). The 54H60 heater is a wire grid embedded in a rubber sheath. FOD results in burn out due to shorted wires and open circuits due to broken wires. Another problem is abrasion of the rubber sheath causing exposure of the heater element. Very critical consideration must be given to the need for blade heaters. It very well may be that they are either not needed or the portion of the blade to be heated can be significantly reduced. If heaters must be used, a more durable heater must be designed to provide resistance to environmental damage.

3.5.3 Recommendations for Future Systems

The study of the baseline reliability data discussed in previous sections clearly indicates that an advanced turboprop propulsion system for the 1990 era should incorporate the following features:

3.5.3.1 On-Condition Maintenance Concept

A design objective of any future system must be the achievement of On-Condition maintenance whereby scheduled overhauls are eliminated and inspections are minimized. This alone has the potential of eliminating 40 percent of the current engine, reduction gear and propeller maintenance cost (reference Figures 3.5.1.1-1 and 3.5.1.2-1). A condition which will facilitate the implementation of this maintenance concept in commercial aircraft service is improved fault detection and isolation via diagnostics to identify impending problems such that corrective action can be taken prior to failure.

3.5.3.2 Improved Modularity

The entire propulsion system must be designed using modular concepts so that failures and resulting removal and repair can be restricted to small equipment packages with little or no disturbance to the rest of the propulsion system thus avoiding additional maintenance/shop costs and the opportunity for maintenance errors.

For example, current commercial propellers offer a minimum of modularity. In the case of the HS 54H60 there are three major modules, the propeller assembly, control or pump housing, and the valve housing. One of these, the pump housing, can only be removed by first removing the propeller assembly. A future system must offer improved modularity. In particular, it must be possible to replace individual blades to reduce the cost of blade maintenance, including heater failures, by minimizing the amount of hardware removed. Further, it should be an objective to delete the need for shop or on-wing balancing. A recommended list of propeller modules in addition to the complete propeller assembly is as follows:

1. Individual blades (Replaced in pairs)
2. Pitch change actuator
3. Pitch change regulator
4. Slip ring assembly

The benefits of modularity include ease of line maintenance, lower line and shop maintenance repair times, and reduced spare parts requirements. These factors in turn reduce aircraft delay times necessitated by component replacement.

Accessory drives should be isolated and modularized so that the engine or reduction gearbox can be removed without removal of most accessories. Also, required maintenance to such modules as accessory drive gearboxes could be performed without removal of the engine or reduction gearbox. The objective must be minimal equipment removal and disturbance to perform a maintenance action.

3.5.3.3 Anti-icing and Improved Blade Heaters

The propulsion system should be critically evaluated to eliminate if at all possible propeller anti-ice features. If this is not possible then blade heaters must be improved. The current 54H60 blade heater is a rubber covered wire heating element which is susceptible to environmental damage (FOD and erosion) and subsequent

heater element failure. An improved heater concept, less susceptible to these problems, must be developed to lower the frequency of heater failures. This in conjunction with improved modularity, allowing individual blade replacements, will have a significant impact on cost related to heaters.

3.5.3.4 Core Engine and L.P. Turbine

The core engine and the L.P. turbine of the advanced turboprop system will make use of those proven technologies that are available today or can reasonably be expected to mature prior to introduction into service. Core engine and L.P. turbine technology generally available to all versions of gas turbine engines can be incorporated into the advanced turboprop system.

3.5.3.5 System Approach

The propulsion system must be designed as a complete propulsion system package. Sufficient definition of such interfaces as accessory drive and accessory units, and the avoidance of sub-optimization would be two benefits.

Maximum ground clearance must be provided by the aircraft design to lessen runway-generated FOD.

A clearly defined on-condition maintenance concept must be developed in conjunction with potential user airlines and the aircraft designers. These concepts would take into account maintenance access times, likely available skill levels and support equipment. Thus the propulsion system, aircraft and airline operations can be designed to derive the benefits of condition monitoring equipment. Such equipment can provide an early indication of malfunction and, especially, pinpoint the specific component needing maintenance thus reducing secondary damage and eliminating unjustified removal of control/accessory components.

3.5.3.6 Improved Hardware Reliability and Durability

Improved hardware reliability must be achieved. Means to accomplish this include hardware simplification as measured by lower parts count, use of improved materials, and the elimination of historical problem areas.

4.0 TASK II - FUTURE TURBOPROP SYSTEMS

The study of future turboprop systems and the selection of an advanced turboprop system for the reliability and maintenance cost projections was based upon an advanced concept being studied by NASA. This concept features a small diameter, multi-bladed, variable pitch propeller, or Prop-Fan, geared to a high-pressure ratio gas turbine engine. It has the potential to be a more efficient thrust producing system than a high bypass turbofan at 0.8 M cruise. In addition to conserving fuel and saving operating expense, it offers the potential of an acceptable cabin environment/low neighborhood noise level, and uncompromised safety.

4.1 Design, Reliability, Maintainability Requirements

Section 4.1 outlines the requirements for future turboprop propulsion systems in the areas of design, reliability and maintenance philosophy. The basic elements of safety, reliability, maintainability, cost, weight, and performance were foremost in the establishment of these requirements. Section 4.3 describes a system that was evolved to meet these requirements.

The basis for these requirements are the results of past experience as concluded in Task I; other experience as documented in Reference 4, and current and anticipated FAR and EPA requirements. The requirements are detailed in Appendix A, "Advanced Turboprop Propulsion System Design Requirements."

4.1.1 Reliability and Life Goals

The reliability and life goals for an advanced turboprop propulsion system were established consistent with safety, a minimum maintenance cost for the mature system, and the overall objectives for a system suitable for commercial airline operation. Preliminary designs, as well as detail designs later, must be carefully prepared to meet the safety, reliability and life requirements.

4.1.1.1 Life Goals

With design life defined as the time or life that the propulsion system shall operate satisfactorily with scheduled maintenance, without scheduled part or component replacements and with unscheduled replacement frequencies no more frequent than are consistent with the stated MTBF values, the following were established:

- Design life of turbine airfoils and control system components = 20,000 hours
- Design life of all other parts = 35,000 hours

4.1.1.2 Reliability Goals

Reliability values established for the system are shown below. These are considered attainable especially when the following concepts and approaches are given a high order of importance:

- Simplified hardware to reduce the number of parts.
- Incorporation of today's State-of-the-Art technology as well as advanced technology.
- Designing durability into areas which historically have shown susceptibility to wear.

Mean Time Between Unscheduled Removal (MTBR) based on propulsion system inherent events shall be no less than those shown in Table 4.1.1.2-I for major modules and in Table 4.1.1.2-II for components. These specific reliability goals were based on the results of this study (Ref. Sect. 4.3.9).

Table 4.1.1.2-I Inherent Reliability Goals for Advanced Turboprop System - Major Module removals

| MAJOR MODULES | INHERENT MTBR, HRS | CORRESPONDING REMOVAL RATE/1000 HRS |
|---|-----------------------|--|
| Core engine | 6,250 | 0.160 |
| LP (Power) Turbine | 50,000 | 0.020 |
| Power Section Accessory Drive Gearbox | 50,000 | 0.020 |
| Main Drive Reduction Gearbox | 33,333 | 0.030 |
| Propeller Disc (Requires Complete Propeller Assembly Removal) | 500,000 | 0.002 |
| Total for Major Modules (Inherent) | 4310 | 0.232 |

Table 4.1.1.2 - II Inherent Reliability Goals for Advanced Turboprop System - Component and Accessory Removals

| COMPONENT OR ACCESSORY | INHERENT MTBR, HRS | CORRESPONDING REMOVAL RATE/1000 HR |
|---|-----------------------|---------------------------------------|
| Power section major accessories (Oil pump, scavenge pumps, fuel pump, ignition) | 50,000 | 0.020 |
| Power section minor accessories | 6,667 | 0.150 |
| Control system | 2,500 | 0.400 |
| Spinner | 200,000 | 0.005 |
| Pitch change actuator | 50,000 | 0.020 |
| Blades, 8 (propeller) | 50,000 | 0.020 |
| Slip ring assembly | 100,000 | 0.010 |
| Pitch change regulator | 20,000 | 0.050 |
| Variable delivery pump | 10,000 | 0.100 |
| Minor propeller components* | 100,000 | 0.010 |
| Starting system | 3,700 | 0.270 |
| Total for components (Inherent) | 950 | 1.055 |

*Forward cover and fairing, deicing conduit assembly, auxiliary pump, transfer tube assembly, and filter.

4.1.2 Maintenance Philosophy

Maintenance Philosophy can be defined as a characteristic of equipment design which facilitates maximum system effectiveness and minimum cost of ownership. To achieve these goals, cost effective maintenance concepts must be designed into the end product during the conceptual and design phases.

The objective for an Advanced Turboprop Propulsion System shall be to achieve reduced maintenance cost through an on-condition maintenance philosophy whereby the objective is to eliminate scheduled maintenance. This shall be facilitated by:

- Improved Reliability - All parts shall be designed for high durability and long life, with particular attention to historical areas of wear.
- Improved diagnostics - Through better fault detection and isolation, less time will be spent in troubleshooting and fewer unjustified removals will occur. Aircraft downtime will also be reduced, and in some instances may be eliminated as a result of being able to schedule the correction of a diagnosed problem.
- Increased Modularity - Increased modularity permits the on-aircraft replacement of a minimum amount of hardware when a failure or impending failure occurs. This reduces the time required for component replacement and also lowers the investment in spare parts in that small modules or components rather than complete assemblies are provisioned. Smaller modules also reduce shop repair costs.
- Simplified hardware (reduced complexity/number of parts) - Simplified hardware results in reduced shop repair times and parts cost as well as fewer cases of shop repair as a result of improved reliability.

The Advanced Turboprop Propulsion System Design Requirements, Appendix A, contains specific design requirements for maintainability. These requirements include the following:

- Design for modularity
- Mounting
- Accessibility
- Repairability
- Inspection/Verification concepts
- Serviceability
- Detail component design requirements for ease of maintenance

The nacelle must provide for maximum access with minimum ramp time to the propulsion system power section for components, module, and complete power section/propeller replacement. Figure 4.1.2-1 presents a nacelle configuration that would meet this requirement.

Figure 4.1.2-2 presents a concept where the advanced propeller can be replaced as a total module requiring minimum disconnects for removal from the main drive reduction gearbox.

Figure 4.1.2-3 illustrates the concept where the advanced propeller and main drive reduction gearbox can be removed as a module.

Figure 4.1.2-4 illustrates a concept for power section removal from the aircraft. With this concept the accessibility to the power section is further enhanced for replacement of components/modules such as the LP turbine.

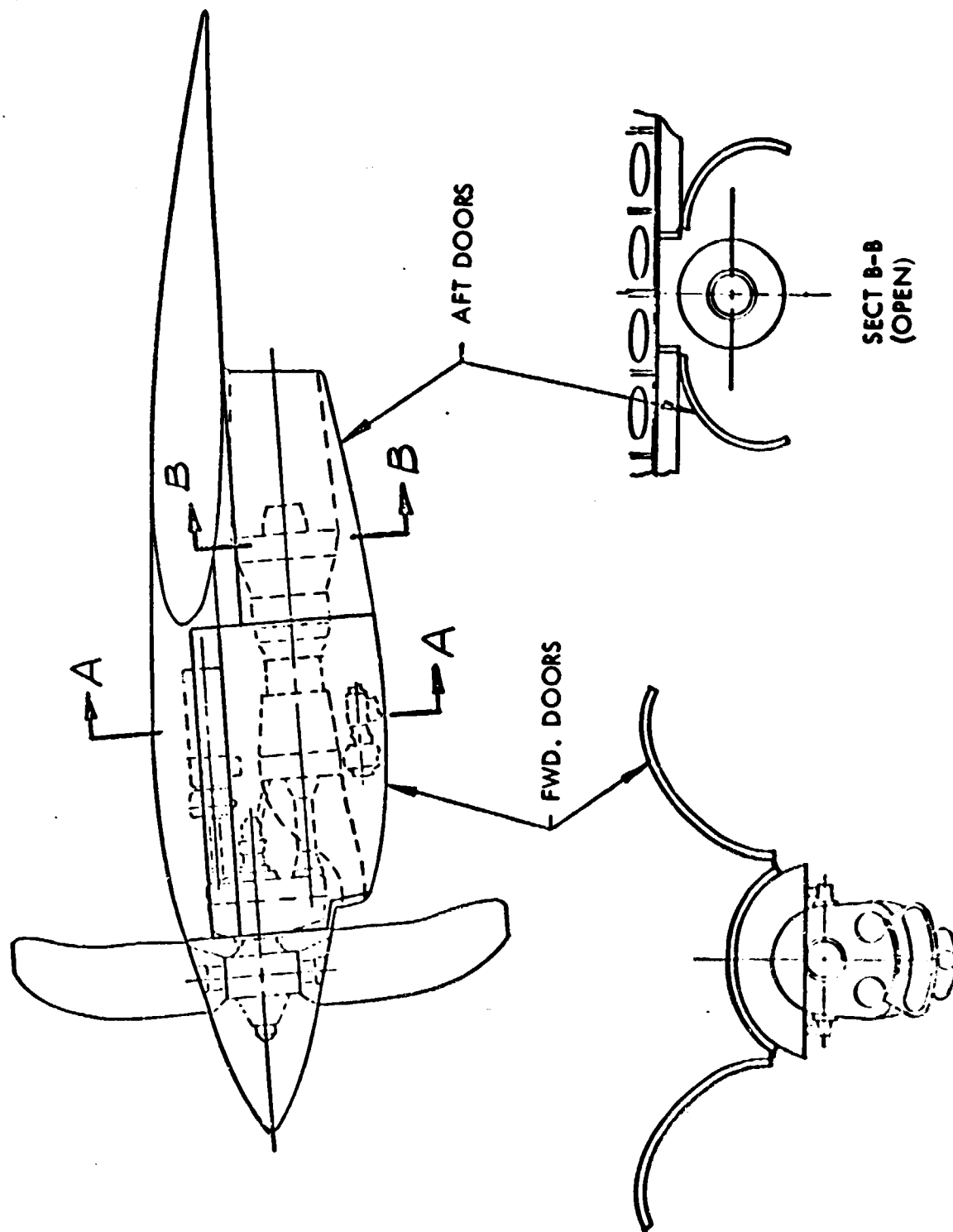
4.1.3 Design Requirements

The design requirements which are discussed in this section are greatly influenced by the experience of airline operators in millions of hours of gas turbine powered aircraft operation, many of them in aircraft powered by DDA turboprop engines. This type of experience has been analyzed and summarized in Reference 4 which was used as a reference in establishing design guidelines for the advanced turboprop propulsion system.

Other guidelines were applicable current Federal Airworthiness Regulations and the results of a study of 501-D13 engine and reduction gearbox and 606/54H60 propeller failure data which highlighted those propulsion system elements requiring improvements or redesign.

Many of the design requirements represent a significant departure from past practice; e.g., the concept of a "Turboprop Propulsion System", under one management, which includes all components of the power package. This concept will facilitate the integration of the propulsion system into the aircraft design and provide the airline operator with a propulsion system which simplifies the servicing and maintenance of the aircraft.

Safety is emphasized with disc and propeller blade designs of high reliability. The engine shall "contain" failed compressor and turbine blades. The control system requirements feature redundancy and such control system emergency features as auto-feathering, feather and reverse blade position stops, and mechanical in-place pitch lock.



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SECT B-B
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Figure 4.1.2-1. Advanced turboprop propulsion system aircraft nacelle concept.

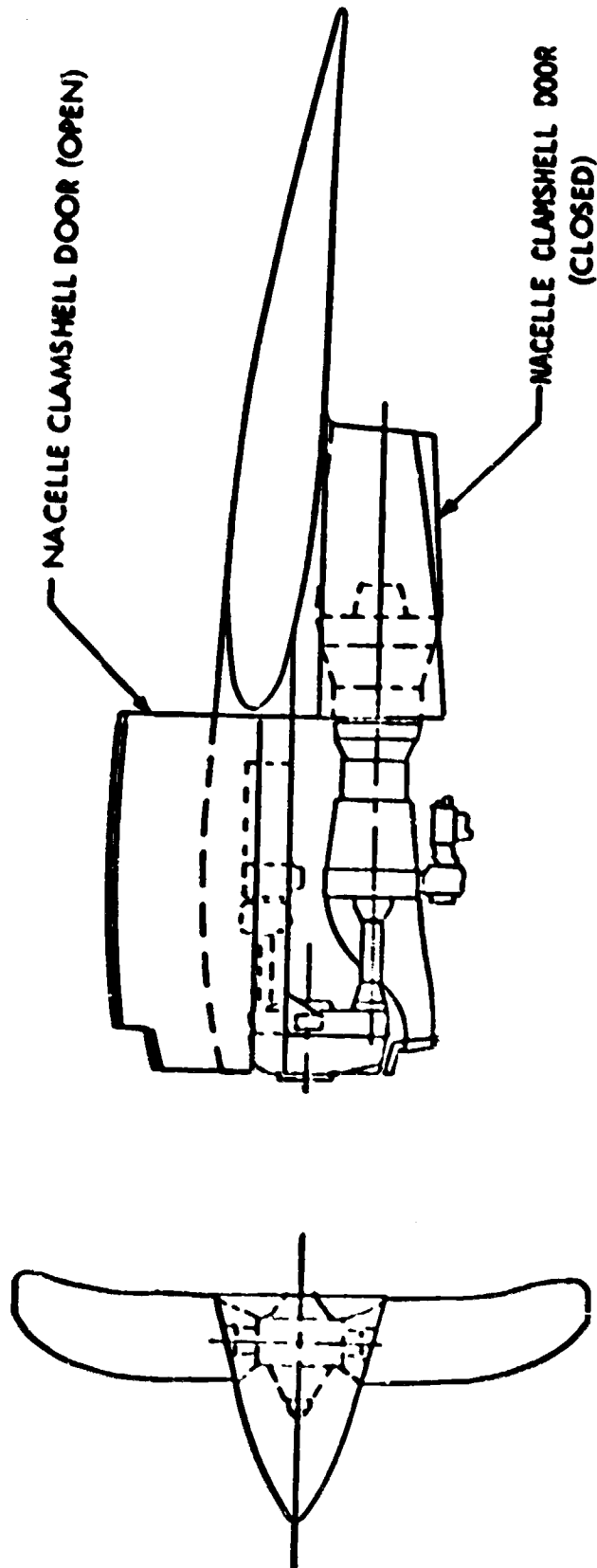


Figure 4.1.2-2. Advanced turboprop propulsion system propeller removal concept.

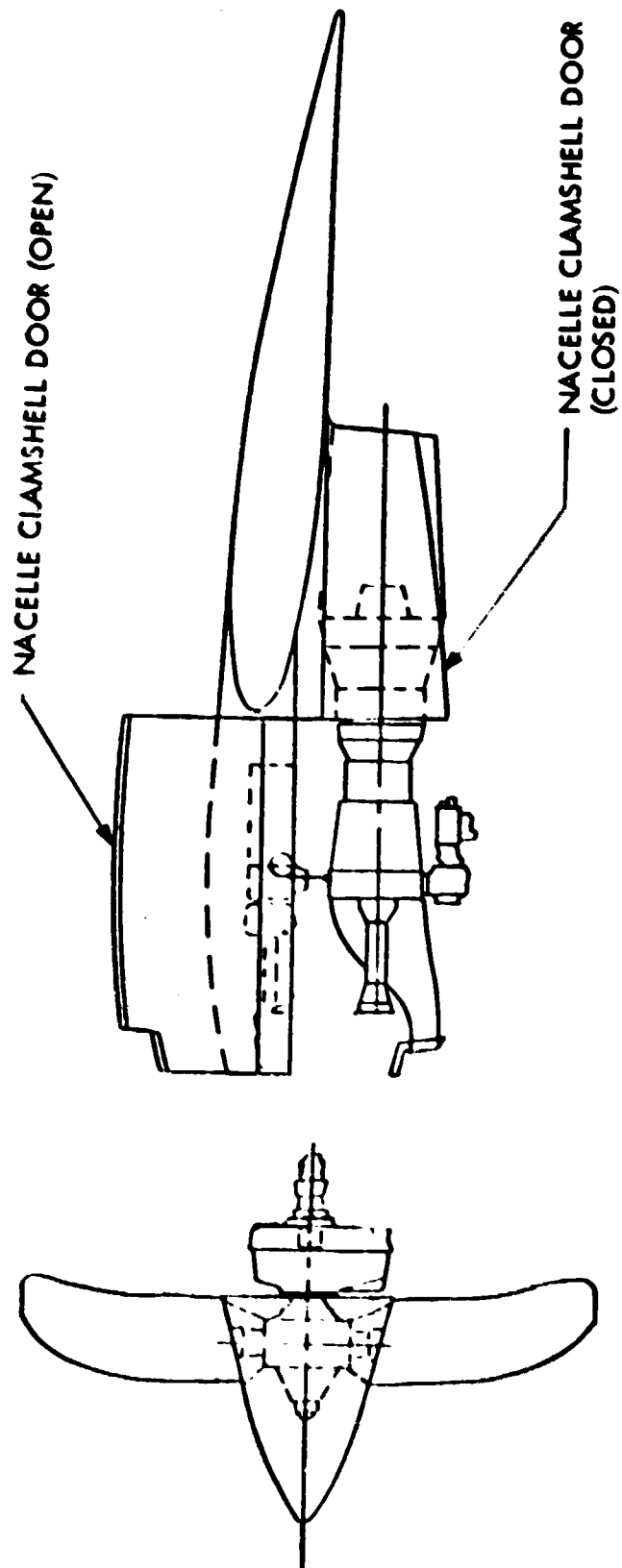


Figure 4.1.2-3. Advanced turboprop propulsion system advanced propeller and main drive reduction gearbox removal concept.

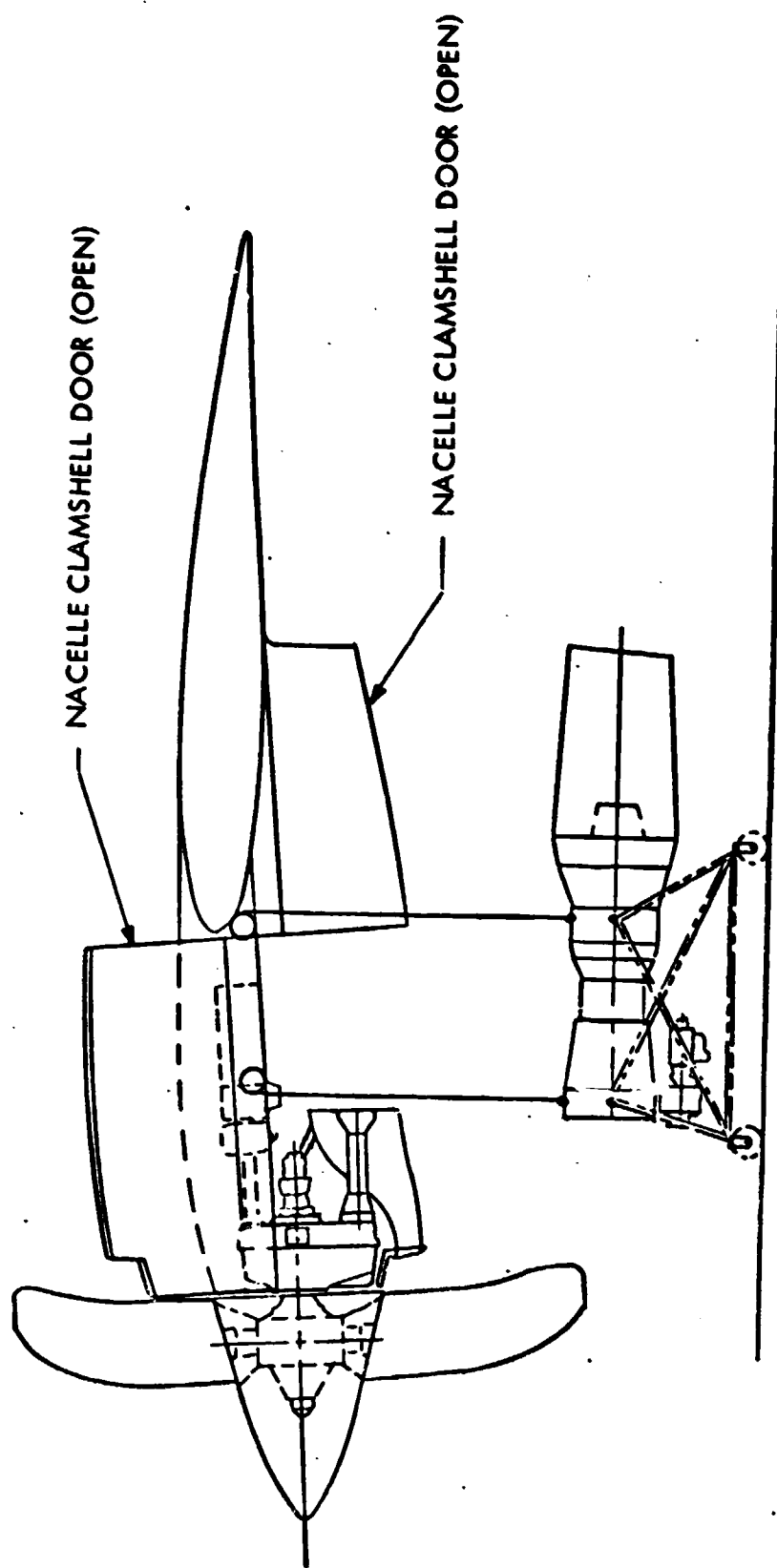


Figure 4.1.2-4. Advanced turboprop propulsion system power section removal concept.

The design requirements for the advanced propeller have, as their basis, proven methods of structural design and pitch control. Innovative implementation of these methods, using the latest technical approaches, results in a concept which eliminates historical problem areas and reduces system complexity.

Other significant design requirements include a new set of noise standards which reduce noise levels below those presently provided for in FAR 36.

Another significant change from previous years is the amount of air pollution which will be permitted. Future standards will reduce acceptable pollution levels considerably. Advanced turbofan and turboprop engines which meet these projected standards will require the introduction of new technologies in the engine design. These may include advanced methods such as fuel staging, variable geometry, and premix/prewrap fuel injection.

One of the fundamental guidelines in preparing these requirements was to improve the maintainability of the total propulsion system. Consequently, prime consideration has been given to all design requirements which have an influence upon maintenance. These include such items as mounting; installation and removal provisions; service line disconnects; ground support attachments; module disassembly and assembly; inspection, adjustment and removal of components; wrench clearance; elimination of special tools; etc. This was also the underlying reason behind the requirement for the separation of accessories. Those accessories required by the propulsion system are driven by and mounted on the propulsion system. The design requirements reflect the desirability of having those accessories required by the aircraft and driven by the propulsion system, be mounted on a separate gearbox remote from the propulsion system. Thus these accessories need not be disturbed when the propulsion system is removed from the aircraft for maintenance.

4.1.4 Design Requirements Document

The requirements discussed in the preceding sections are presented in more detail in a "Design Requirements" document, which forms Appendix A of this report. These requirements are generalized, such that they do not relate to any specific engine or propeller model, and are based upon current F.A.R. and E. P. A. requirements. Modification of the requirements document could be expected as a result of:

- Detailed follow-on discussions with potential user airlines
- Revisions made or anticipated in F. A. R. and E. P. A. regulations

4.2 Ratings for Advanced Turboprop Propulsion System

In sizing the advanced turboprop for this study the following guidelines were established:

- The cruise thrust level at 0.8M at 35,000 feet altitude should be comparable to at least one of the turboprop systems selected by Lockheed, Boeing, or Douglas in their NASA funded RECAT studies as these systems represented typical future turboprop usage.
- It was desirable that the cruise thrust level be close to one of the engines in the JT8D family for purposes of maintenance cost comparisons.
- The DDA Model PD370-22 advanced turboprop engine and the Hamilton Standard Prop-Fan would be used as base-line advanced concepts from which scaling, or sizing, would be made to meet the thrust requirements.

Comparing JT8D cruise and climb thrusts at 0.8M at 35,000 feet altitude with the results of the RECAT studies, it was found that the Lockheed RECAT concept (Reference 2), a four-engined advanced turboprop airplane, required thrusts per engine that fell within the thrust output of the JT8D family. The required installed climb thrust was approximately 3500 lbs.

Hamilton Standard's recommendations for sizing a Prop-Fan have always included a high cruise power loading ($\text{SHP}/\text{Diameter}^2$), generally about three times that of a conventional turboprop such as that used on the Lockheed Electra. This specific recommendation was based on achieving the following objectives: 1) a high cruise propulsive efficiency significantly better than that of a comparable technology high bypass turbofan, 2) takeoff thrust significantly better than the high bypass turbofan, and 3) a rotor diameter which is much smaller than that of a conventionally loaded propeller. A compact turboprop propulsion system inherently has simplified installation problems, a beneficial impact on the geartrain torque and gear ratio, and structural dynamic benefits.

Advanced turboprop propulsion system studies conducted to date by both engine and airframe manufacturers have used the high rotor loading concept and also have indicated that the Prop-Fan, unlike the turbofan, is sized by the cruise thrust requirement rather than the takeoff thrust requirement. Hamilton Standard's recommended power loading of $37.5 \text{ SHP}/\text{D}^2$ at 800 feet per second tip

speed, 0.8 Mn, 35,000 feet altitude, maximum climb is considered representative of the power loadings selected by Pratt & Whitney, General Electric, Lockheed, Boeing, and Douglas in their NASA funded advanced turboprop studies.

Using the DDA Model PD370-22 (unity size) maximum climb power at 0.8 Mn and 35,000 feet with the HS recommended power loading yields a 12.8 foot diameter Prop-Fan. Specifically the calculation is:

$$\text{Dia.} = \left(\frac{\text{SHP}}{37.5} \right)^{1/2} = (6126/37.5)^{1/2} = 12.78 \text{ feet}$$

The net (uninstalled) thrust from the Prop-Fan based on 80 percent efficiency, is 3465 pounds and the jet thrust from the core is 502 pounds. This 3967 pounds of thrust, uninstalled, compares quite favorably with the uninstalled max climb thrusts of the JT8D-7 and JT8D-9 engines at 35,000 feet and 0.8 M, and the thrust requirement of the Lockheed RECAT study. This sizing was accomplished on an uninstalled basis since studies have shown that the installation losses of a turbofan and advanced turboprop should be approximately equal. The maximum SHP/D² is determined by the power lapse rate of the engine. For the PD370-22, the maximum shaft power of 13345 occurs at 0.3 Mn, Sea Level, 90 deg F conditions.

Therefore the unity size DDA Model PD370-22 power section and a Hamilton Standard 12.8 ft, 8-bladed Prop-Fan formed the basis of the advanced turboprop propulsion system of this study. The specific performance for the selected system is shown in Table 4.2-I.

The PD370-22 power section is an axial flow system, having a single spool core and a free power turbine. It represents an advanced turboprop power section with 25:1 overall pressure ratio. It incorporates demonstrated advanced technologies as well as basic shaft and bearing arrangements from the new T701 turbo-shaft engine. The power section general arrangement in unity size is shown in Figure 4.3.1-2. Output speed is 9545 rpm. The main drive reduction gear ratio is 7.95:1 providing a Prop-Fan speed of 1200 rpm. In unity size the power section has a length of 82.5 inches and a max diameter of 34.2 inches. The weights of the advanced power section, main drive reduction gear and

Prop-Fan are as follows:

| <u>Module</u> | <u>Weight, lbs.</u> |
|------------------------------|---------------------|
| Prop-Fan | 1298 |
| Main Drive Reduction Gearbox | 887 |
| Power Section (PD370-22) | 1566 |
| Total Uninstalled Weight | 3751 |

TABLE 4.2-I

ADVANCED TURBOPROP PROPULSION SYSTEM RATINGS

100% Recovery
Zero Power Extraction & Bleed
12.78 Feet Prop-Fan Diameter

| <u>Condition</u> | <u>Mach</u> | <u>Altitude</u> | <u>Temp</u> | <u>SHP (PD370-22)</u> | <u>*T_{net}</u> | <u>**F_n</u> |
|------------------|-------------|-----------------|-------------|---------------------------|-------------------------|------------------------|
| Takeoff | 0.1 | SL | 90 Deg F | 12638 | 16137 | 1608.3 |
| Takeoff | 0.2 | SL | 90 Deg F | 13060 | 14416 | 1397.7 |
| Takeoff | 0.3 | SL | 90 Deg F | 13345 | 12884 | 1197.6 |
| Climb | 0.8 | 30,000 ft | Std. Day | 7345 | 4074 | 532.8 |
| Cruise - max | 0.8 | 30,000 ft | Std. Day | 6917 | 3875 | 453.8 |
| Climb | 0.8 | 35,000 ft | Std. Day | 6126 | 3465 | 501.5 |
| Cruise - max | 0.8 | 35,000 ft | Std. Day | 5847 | 3316 | 445.6 |

*Prop-Fan Thrust in Pounds

**Core Jet Thrust in Pounds

4.3

Design Description of Future System

This section describes an advanced turboprop propulsion system which meets the requirements outlined in Section 4.1 and presented in detail in Appendix A, Advanced Turboprop Propulsion System Design Requirements. The system embodies advanced system concepts that include a Hamilton Standard Prop-Fan and a DDA power section and main drive reduction gearbox with an integrated electronic control system. The advanced concepts have been particularly directed toward minimization of maintenance costs.

In order to realize the full potential of the turboprop propulsion system it would be essential that the management of the system be the responsibility of a single propulsion system manager. The propulsion system design would be the result of a team effort, with team members representing the engine manufacturer, the propeller manufacturer, the airframe manufacturer, and one or more airline operators. The team manager would be the engine manufacturer representative, who also has the bulk of the hardware responsibility. This approach would permit a coordinated design which should minimize interface problems and optimize the functional requirements of the total propulsion system. The team approach would also permit a rapid response to in-service problems, by virtue of a predetermined definition of the required corrective action. In an actual installation, a problem response flow diagram would be evolved, to specify the problem-responsible team member, and the corrective actions to be taken, for all problem categories. This predetermined action plan would be designed to minimize the response time for correction of in-service problems, as well as the maintenance cost per flight hour of on-line operation. This management concept is a distinct improvement over previous powerplants such as the 501-D13/606 system, in which each of the engine, propeller, and QEC modules was under the jurisdiction of a separate development manager.

The following paragraphs describe the details of this propulsion system as currently envisioned and which is the basis for the related weight, production cost, and mature maintenance cost projections.

4.3.1

Propulsion System Arrangement

The overall arrangement of the propulsion system is shown schematically on Figure 4.3.1-1, as it would be installed on an aircraft wing. The complete propulsion system, in agreement

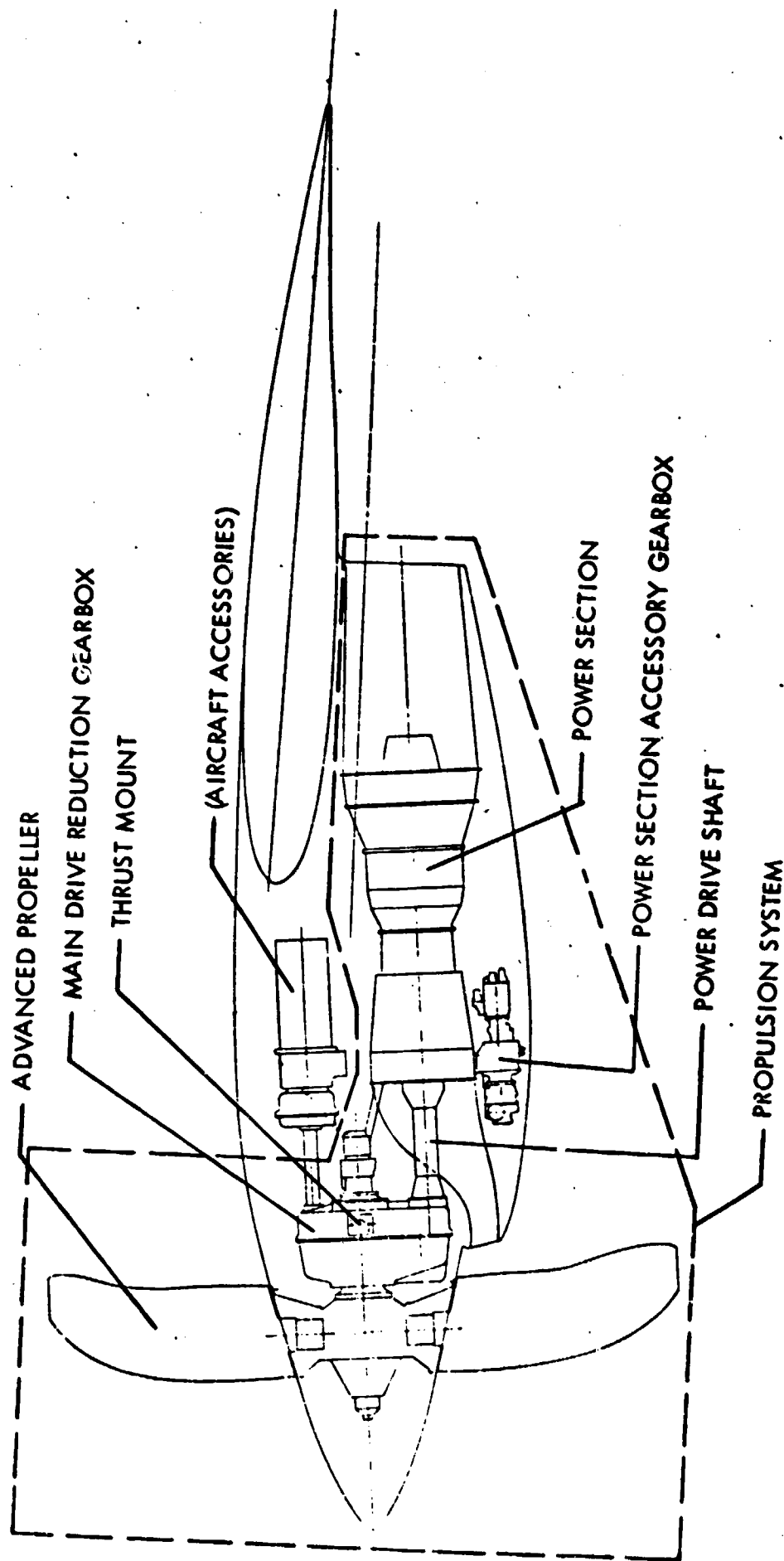


Figure 4.3.1-1. Advanced turboprop propulsion system general arrangement.

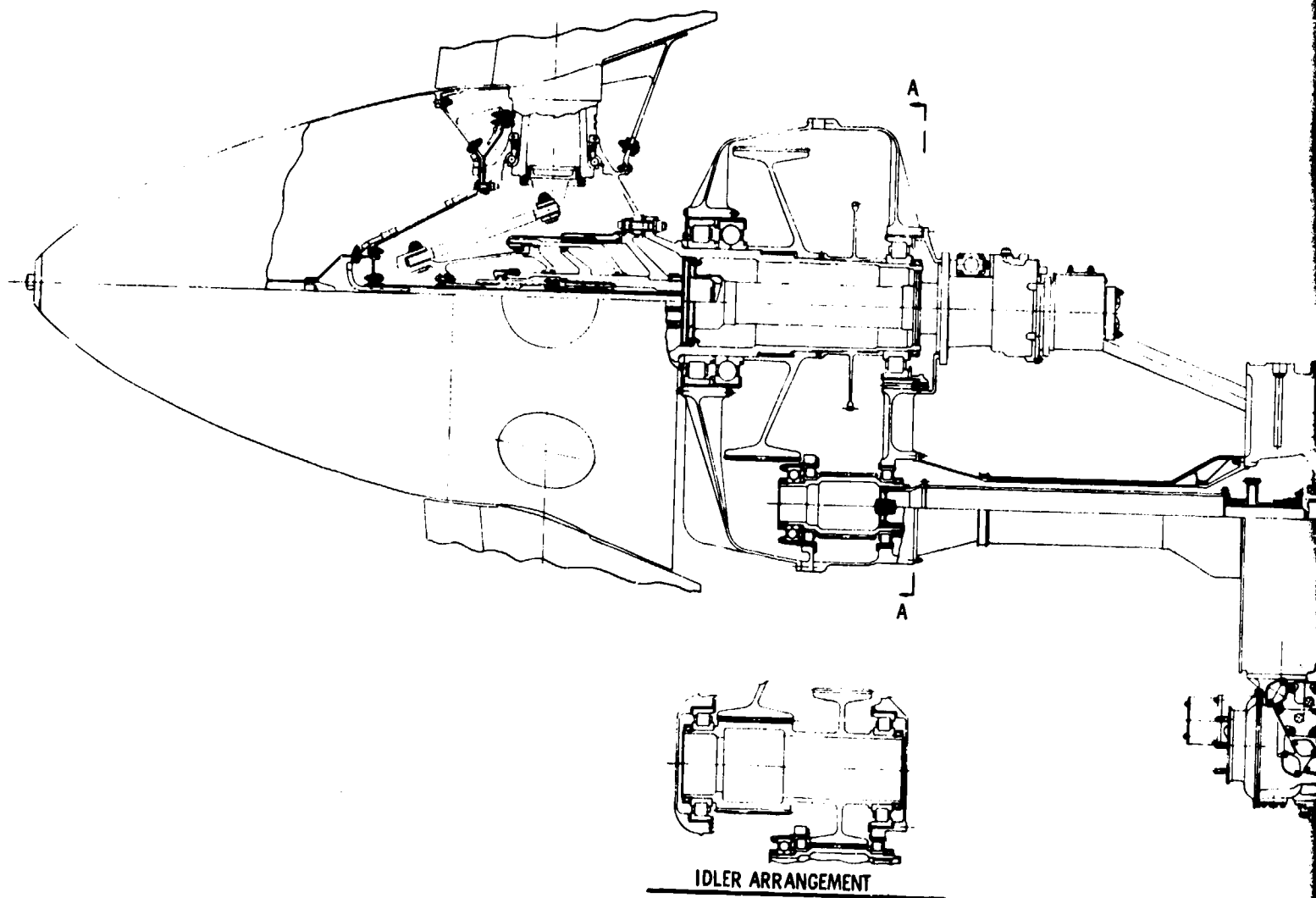
with paragraph 1.0 of the design requirements document (Appendix A), consists of the advanced propeller (Prop-Fan), the main drive reduction gearbox, the power section, and the installation parts. Figure 4.3.2-1, shows a cross-section of the system less installation parts.

4.3.1.1 Installation Parts

The installation parts are those items which adapt the three major modules to the aircraft nacelle. As envisioned, the aircraft nacelle would include two pairs of access doors which open to expose the removable propulsion system. No propulsion system components could be mounted directly on these doors. Installation parts would include the inlet and exhaust ducts, oil cooler, oil tank, firewall, fire detection and suppression system, and any other system components which could logically be included on the propulsion system assembly. A complete list would require a carefully coordinated detail design and installation study for each specific aircraft installation that would include the required disconnects between interconnected systems which are included in both the aircraft and propulsion systems. These would include the fuel system, starting air ducts, electrical systems, and the drive shaft for the aircraft-mounted accessory gearbox. The electrical system disconnects would include the power section condition monitoring signals, instrumentation leads, and external power and control system signals. There would also be an interface connection in the oil cooler inlet and outlet ducting, since the oil cooler is a part of the propulsion system, where the ram air intake is in the fixed section of the nacelle, and the exhaust port would probably be in one of the access doors which form the sides of the nacelle.

4.3.1.2 Mounting and Handling Provisions

The complete propulsion system can be mounted in the aircraft nacelle at two axial locations; two front mount pads, one on each side of the main drive reduction gearbox to absorb thrust and torque loads, and a rear mount on the rear support of the power section which reacts vertical loads while permitting axial thermal expansion. In addition to the primary mount points of this concept, the power section would be equipped with auxiliary handling points which would permit the main drive reduction gearbox, and/or power section, and installation parts to be mounted on transport dollies, or to be hoisted into the nacelle for attachment to the primary mounts. The advanced propeller (Prop-Fan) module is attached to the main drive reduction gearbox after



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Figure 4

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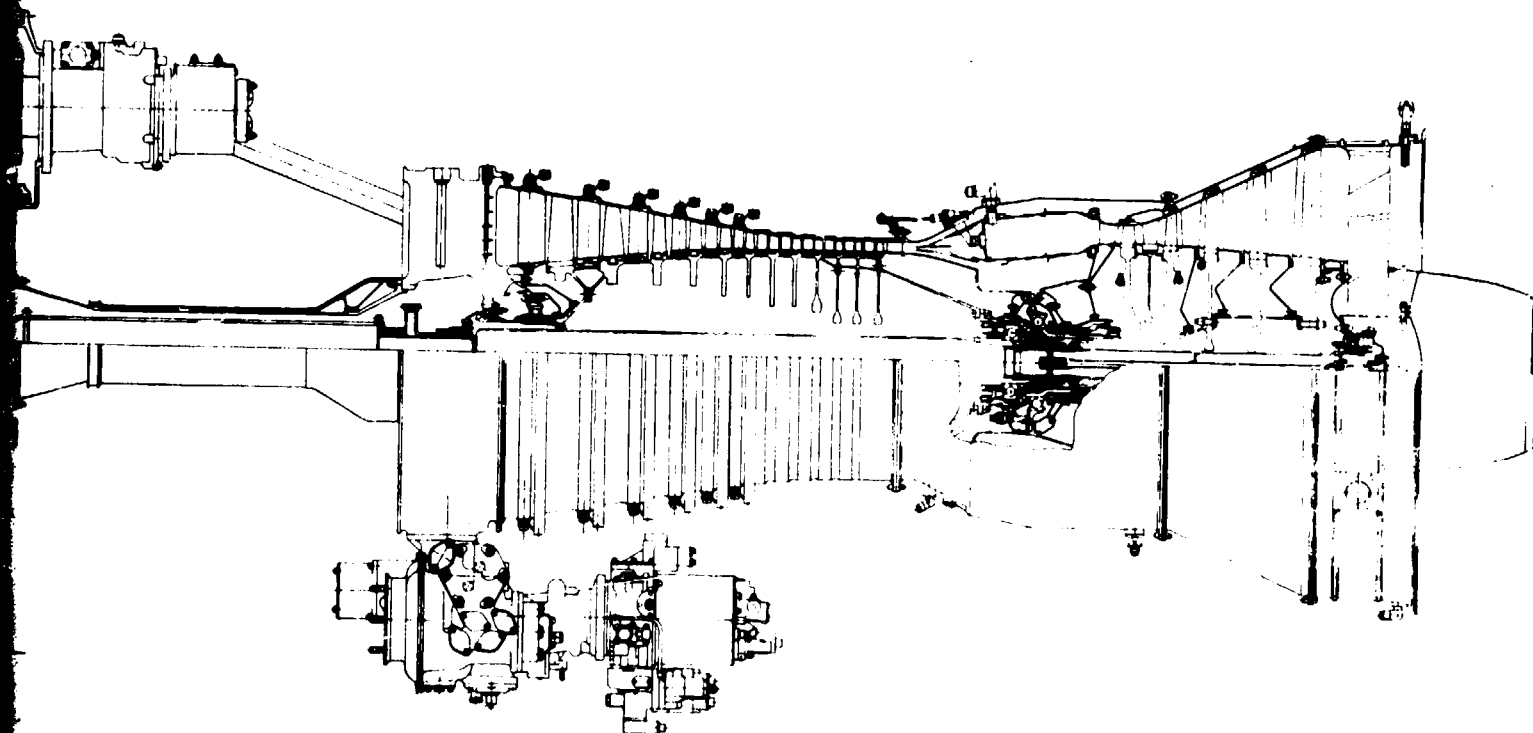


Figure 4.3.1-2. Advanced turboprop propulsion system -
less installation parts.

the other modules have been installed in the nacelle and is removed separately prior to removal of the other modules. This requirement is dictated by the diameter and number of blades on the advanced propeller (Prop-Fan) assembly. This sequence is described in detail in the maintainability section of this report (Section 4.3.8). This or other mounting or handling concepts should exploit the inherent advantages of the modularity of the propulsion system.

4.3.2 Advanced Propeller (Prop-Fan)

4.3.2.1 Design Description of the Prop-Fan

The Prop-Fan is a shroudless propeller utilizing advanced aerodynamic technology to produce a significantly higher propulsive efficiency at high cruise speeds (0.8 M) than can be achieved with a shrouded fan (turbofan). The Prop-Fan selected for this study is 12.8 feet in diameter, has eight blades and operates at 1200 RPM and 13,345 maximum SHP. Modular design of highly reliable components with on-condition maintenance and on-line diagnostics combine to dramatically reduce maintenance costs. Following is a description of each of the major components of the Prop-Fan, shown in Figures 4.3.2.1-1 and 4.3.2.1-2.

4.3.2.1.1 Blade

The Prop-Fan blade, shown in Figure 4.3.2.1.1-1 is of light-weight spar/shell construction similar to present propeller blades in production at Hamilton Standard. A composite material shell is bonded to a structural spar with a honeycomb filler material bonded in the cavities. An erosion coating and metal leading edge sheath are used for improving resistance to erosion and FOD. An advanced technology metallic sheet-type deicer heating element, shown in Figure 4.3.2.1.1-2, is also bonded to the leading edge and is connected to two slip rings on the blade shank as part of the blade ice control system. A single-row ball bearing race and a lip seal are mounted on the inboard end of the spar for blade retention and lubrication oil sealing, respectively.

Blade trunnion arms are splined to the inboard end of the blade spar and the trunnion arms connect with the pitch change actuator links to rotate the blades about the pitch axes.

4.3.2.1.2 Disk and Fairing

The one piece disk is made of steel and is the support structure

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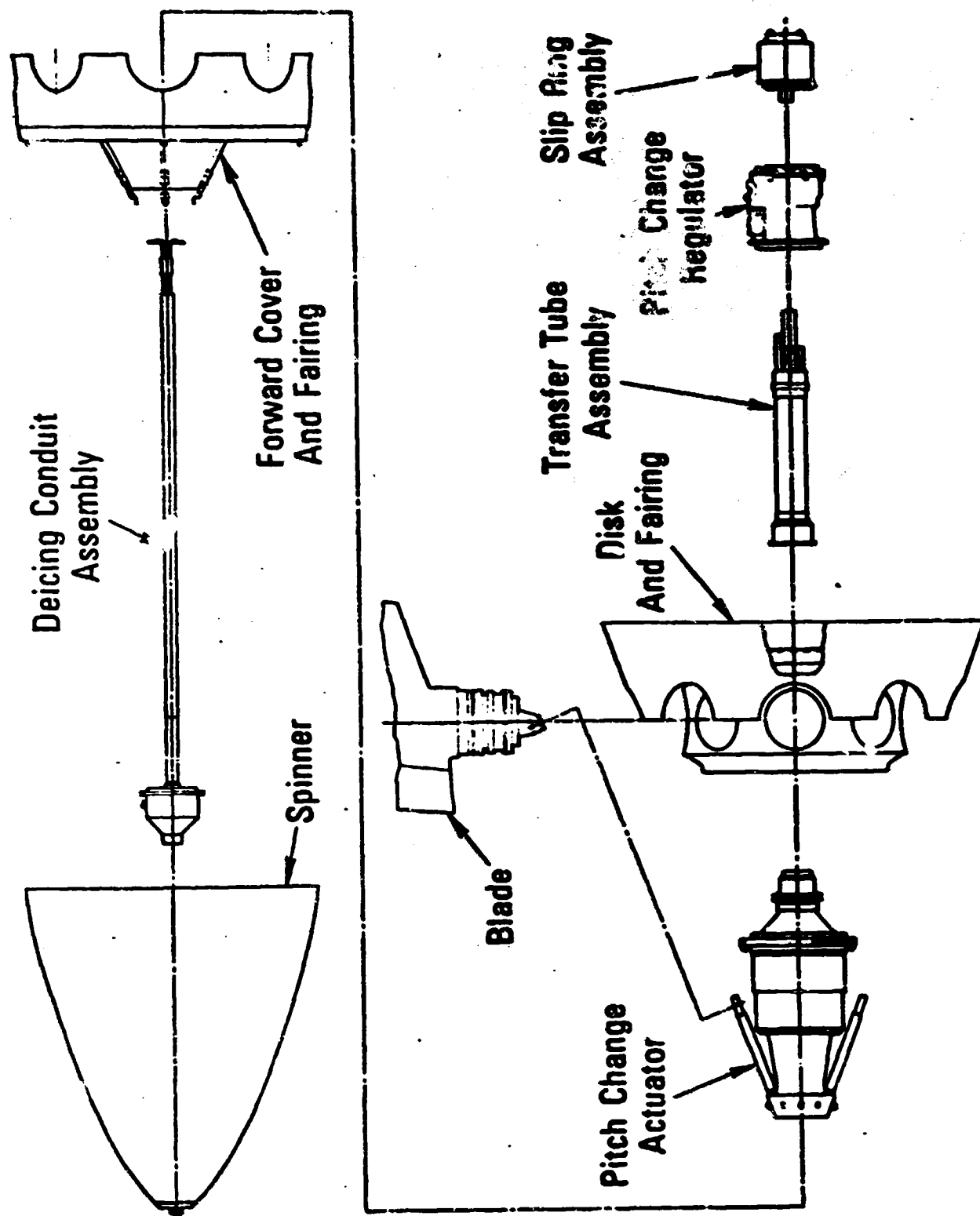
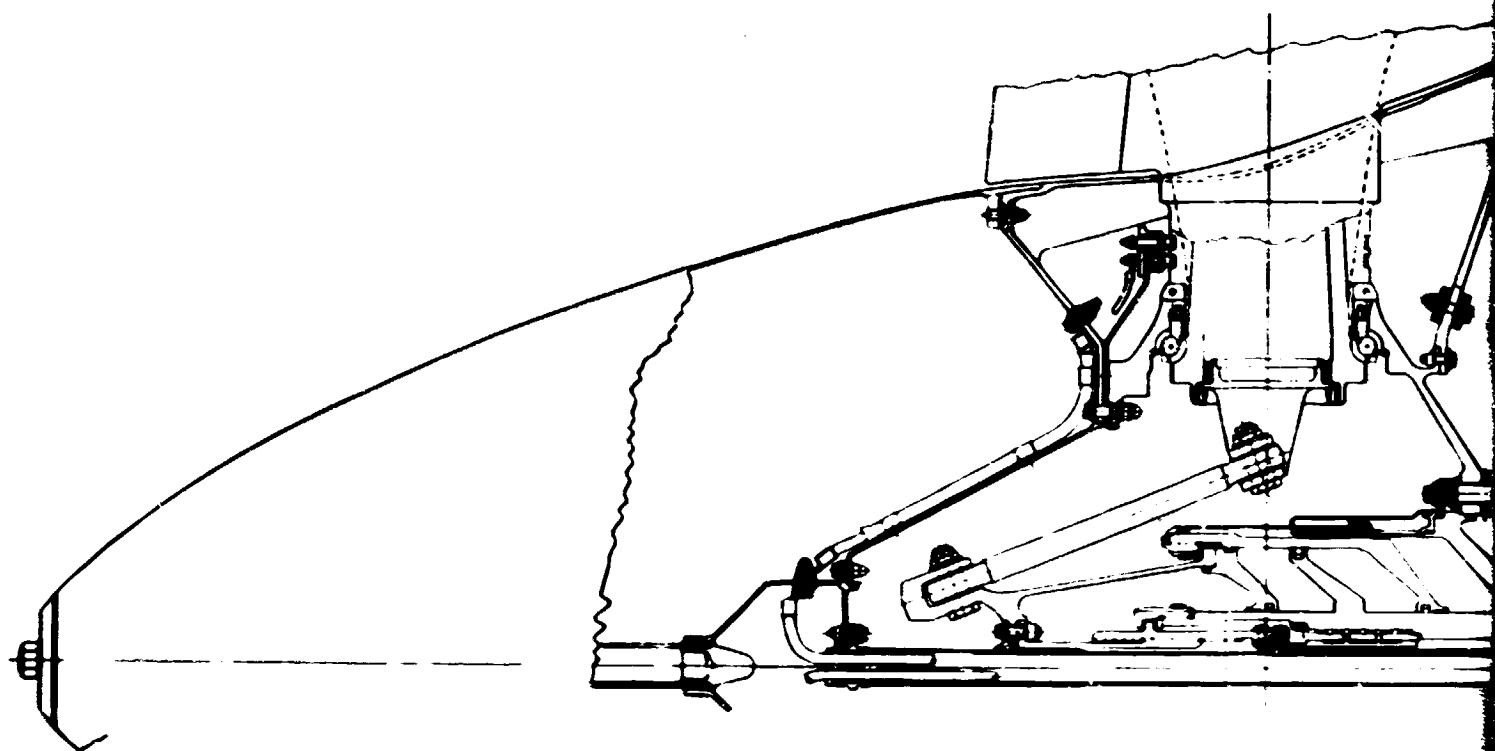


Figure 4.3.2.1-1. Prop-Fan modular design.



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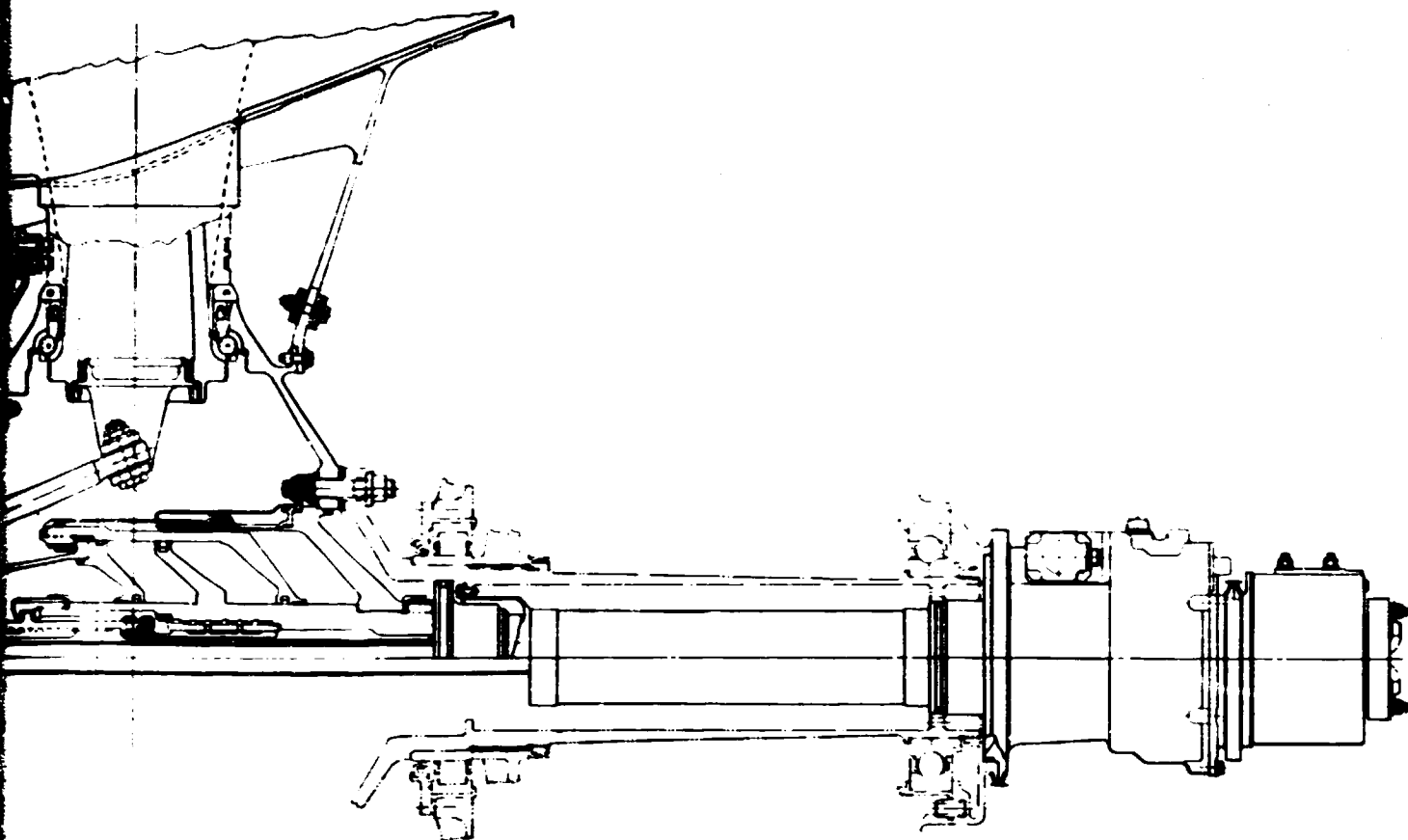


Figure 4.3.2.1-2. Prop-fan Concept

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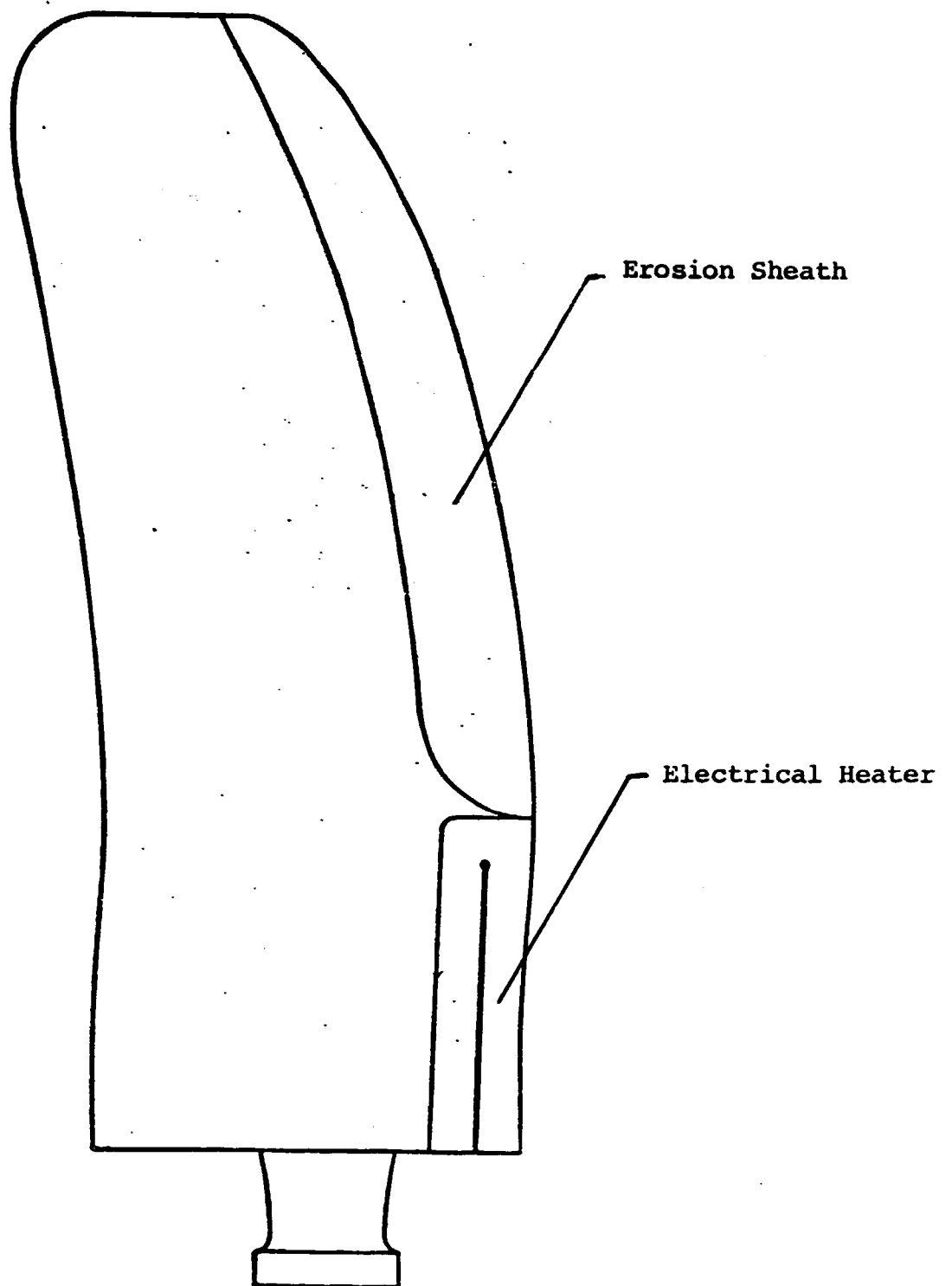


Figure 4.3.2.1.1-1. Prop-Fan blade concept.
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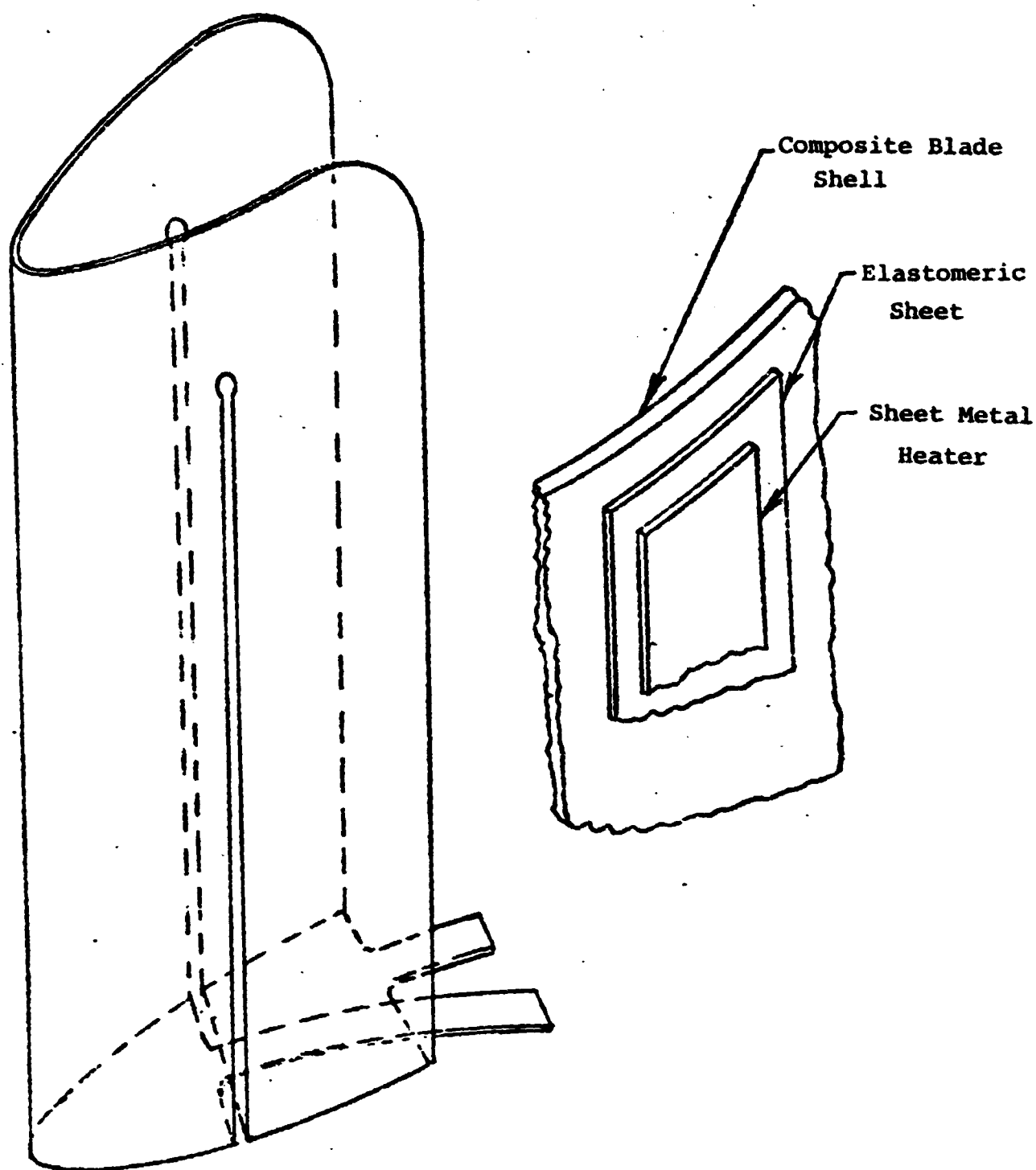


Figure 4.3.2.1.1-2. Blade heater.

for the blades, pitch change actuator, spinner, forward cover and fairings. It is flange-mounted to the reduction gearbox output shaft through curvic face splines. The curvic splines make an efficient joint for driving the Prop-Fan, for quick removal, and for centering to maintain balance control. A single row ball bearing race and balls installed in each blade mounting hole retains the blade in the disk with assistance from an external blade clamp for static support. The retention bearings are lubricated with a fixed amount of oil carried in the disk. The fiberglass rear spinner fairing is bolted to an external bolt pattern on the rear of the disk. Access holes are provided in the bulkhead at each blade to facilitate inspection and maintenance of blade brushes.

4.3.2.1.3 Pitch Change Actuator

The pitch change actuator consists of a linear hydraulic piston-type actuator, beta control valve, blade drive links, a mechanical in-place pitch lock, an input shaft and an oil transfer housing. The pitch change actuator is flange-mounted to the disk with a bolt circle and a centering pilot diameter on the axis of rotation. The actuator piston is fixed to the disk through the mounting flange. The actuator cylinder, which supports the blade link drive ring and pitch lock screw, translates to change pitch through the links. Torque on the cylinder imposed by link forces is reacted by a sliding spline sleeve fixed to the disk.

The beta valve sleeve is fixed to the piston and the valve spool is connected to the cylinder through the pitch lock nut. Rotation of the nut by the input shaft translates the valve spool through a small pitch lock gap, which is equivalent to one degree of blade angle change, metering pressurized oil to cause the cylinder and valve spool to move in the opposite direction thereby nulling the valve. Lap fit leakage from the valve spool lubricates the cylinder torque spline and the pitch lock screw and is returned to the pitch change regulator to be scavenged back to the central oil reservoir. The oil transfer housing transmits supply oil from transfer tubes to the beta valve sleeve through drilled passages in the piston. Return oil from the valve sleeve is also transmitted to return transfer tubes by the transfer housing. Quick-disconnect poppet valves are mounted at each housing port interfacing with a transfer tube. These valves close when the tubes are removed to trap fluid in the actuator for dry actuator removal.

4.3.2.1.4 Transfer Tube Assembly

The transfer tube assembly incorporates four tubes, two supply and two return, to transfer pitch change oil between the pitch change regulator and the pitch change actuator. The tubes are sealed at both ends by "O" ring packings with back-up rings. A torque tube, splined at each end, is also included in the tube assembly. Its function is to transmit a rotary pitch change signal between the regulator and the actuator. All tubes are supported radially and trapped axially in an outer tubular housing. The outer housing is flange-mounted with screws to the forward end of the reduction gearbox shaft and is supported radially at the rear end of the shaft for easy forward removal as an assembly.

4.3.2.1.5 Pitch Change Regulator

The pitch change regulator is mounted at the rear of the reduction gearbox by a single coupling clamp to facilitate line maintenance. The basic functions of the regulator are:

- (a) to transfer actuator supply and return oil across the rotational interface,
- (b) to convert the input electrical pitch change signal from the Full Authority Digital Electronic Control (FADEC) to an output rotary mechanical signal to the actuator and
- (c) to provide a blade position electrical feedback signal to FADEC.

Figure 4.3.2.1.5-1 is a schematic showing the major pitch change regulator components. Function (a) is accomplished by an oil transfer bearing with supply and return sealing lands. The transfer bearing is self-lubricated by its lap fit leakage which is in turn used to splash-lubricate other moving parts in the regulator.

The electrical pitch change signal from FADEC is converted to rotation, function (b), by an electrohydraulic valve (EHV) which meters pressurized oil to either side (direction) of a servo gear motor as a function of input voltage level and polarity. The motor transmits rotation across the rotating Prop-Fan interface through a differential planetary gear set to drive the torque tube in the transfer tube assembly. Since the servo motor is connected mechanically to the blades through

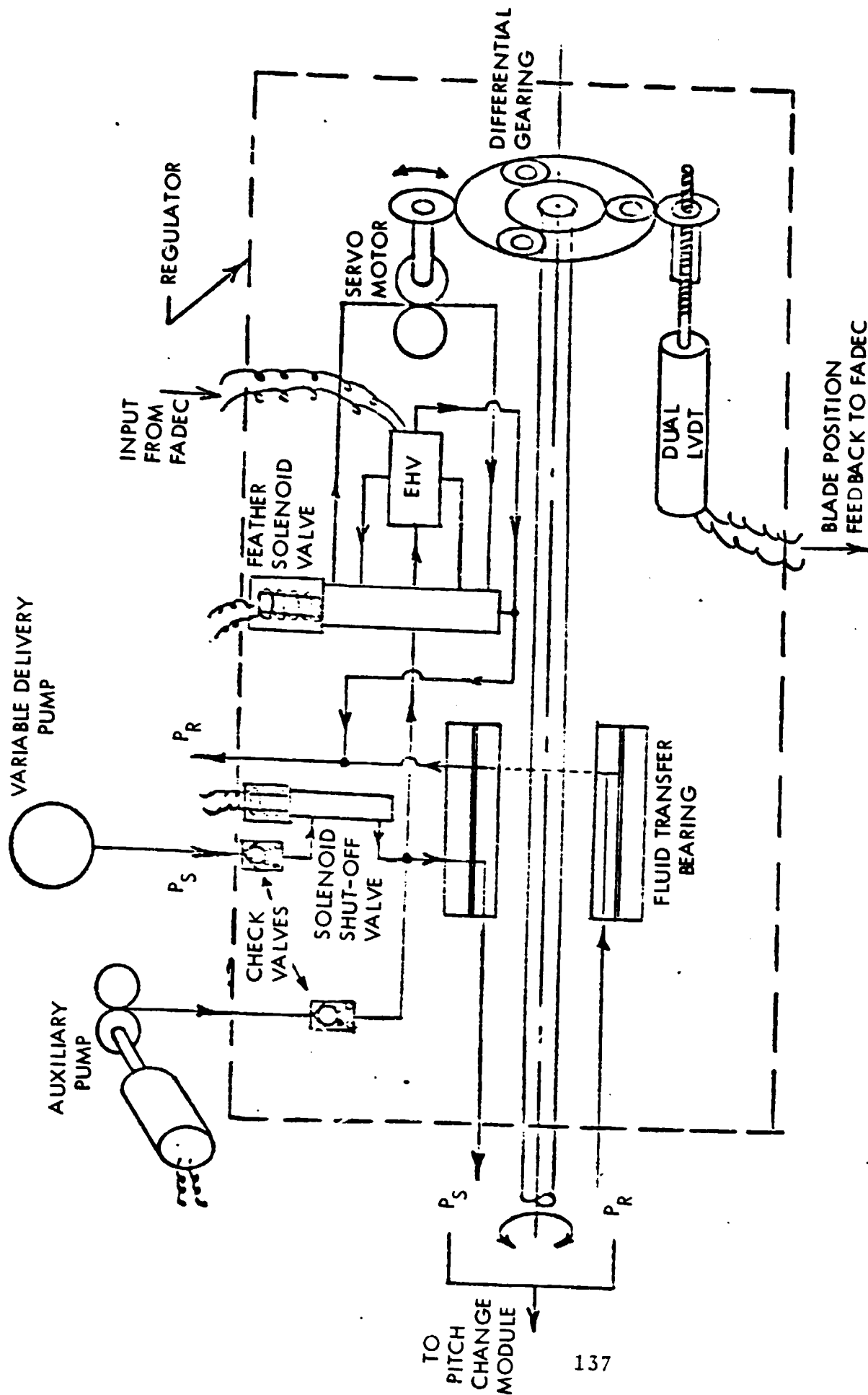


Figure 4.3.2.1.5-1. Pitch change regulator schematic.

shafting to the pitch lock screw in the actuator, motor revolutions represent blade position and are counted electrically to satisfy the blade position feedback signal, function (c). Dual redundant linear variable differential transformer (LVDT) cores are translated by a fine-pitch screw assembly driven by a servo motor driven gear set. LVDT output voltage is calibrated versus blade angle and provided as an input to FADEC.

The regulator has an auxiliary supply oil line to the increase pitch side of the servo motor through a feather solenoid valve for feathering the blades. A solenoid shutoff valve is located in the supply passage to the transfer bearing to permit FADEC or the pilot to lock pitch by shutting off supply oil. There are three hydraulic connections to the regulator: main oil supply, auxiliary oil supply and oil return. Four electrical connectors are associated with the LVDT's, EHV, feather solenoid and shutoff solenoid.

4.3.2.1.6 Slip Ring Assembly

The slip ring assembly is a small-diameter drum type slip ring and brush block assembly used to transmit electrical blade de-icing power across the rotational Prop-Fan interface. The slip ring drum is mounted on grease-packed ball bearings in the brush block ring which is attached to the pitch change regulator by a single coupling clamp for ease of removal. A rotating shaft seal located in the regulator rides on the slip ring drum to seal the slip ring assembly from lube oil. Power from two phases of the aircraft 115-volt three-phase alternator is transmitted through multiple brushes on two power rings and two ground rings.

4.3.2.1.7 Deicing Conduit Assembly

The deicing conduit assembly transmits electrical power from the slip ring assembly through four wires to the Prop-Fan forward cover. The assembly consists of a conduit tube housing the wires, forward support bulkhead, and spinner retention cone. A spline and seal in the slip-ring-drum mates with a matching spline on the rear end of the conduit to drive the slip-ring-drum. Drive torque is reacted on the forward end of the conduit by a torque lug engaged with the support bulkhead. The lug also provides axial constraint for the conduit. Radial support is provided by a seal land in the actuator which translates over the conduit and seals lube oil from entry to the disk.

The spinner retention cone has four terminals, to which the wire terminal lugs are connected, in addition to an internal thread to engage the spinner attachment bolt. The cone and support bulkhead are unitized for ease of handling.

4.3.2.1.8 Forward Cover and Fairing

The forward cover and fairing is bolted on the forward disk face and includes a conical cover, a mid-spinner fairing and bulkhead, a bulkhead that supports blade brush assemblies and a deicer wiring harness. The cover and bulkheads are unitized for ease of handling. The cover seals blade retention oil in the disk, supports the forward end of the deicing conduit assembly and mounts four wires that connect terminals on the conduit assembly with terminals on the mid-fairing bulkhead. The fairing and bulkhead support the rear end of the spinner and fair the spinner contour with the blades and aft spinner fairing. Access holes in the bulkhead at the blades permit inspection and maintenance of the blade brush block assemblies. The deicer wiring harness is clamped to the bulkheads and connects bulkhead terminals with blade brush block terminals.

4.3.2.1.9 Spinner

The spinner provides the aerodynamic shape of the forward end of the nacelle to guide air to the Prop-Fan blades and to the engine inlet for best performance. The spinner is clamped with a small diametral interference fit against the forward cover fairing by a single nose attachment bolt.

4.3.2.1.10 Miscellaneous Remotely-Mounted Components

The following remotely-mounted components interface with the Prop-Fan components that were shown in Figure 4.3.2.1-1.

● Full Authority Digital Electronic Control (FADEC)

The FADEC is an integrated control system which utilized current digital electronic technology to coordinate the power section and Prop-Fan control functions throughout the various flight and ground handling modes. Synchrophasing and auto-feathering are included in the normal control logic. FADEC electrically commands blade angle position to the pitch change regulator and receives blade angle position feedback from the pitch change regulator. The FADEC module is mounted in a readily accessible nacelle location and is easily replaced. A description of FADEC is presented in Section 4.3.5 of this report.

- Hydraulic Variable Delivery Pump

This is a variable-displacement piston pump mounted on the main drive reduction gearbox to supply, on demand, oil pressurized to 3000 psi maximum to the pitch change regulator. The supply for this pump is the central oil system.

- Auxiliary Pump

The auxiliary pump is a small electric motor driven gear pump which supplies pressurized oil from a reserve section of the central reservoir to the pitch change regulator for feathering, unfeathering, and static ground check operation.

- Deicing Timer

The deicing timer regulates 115-volt A.C. electrical power from the aircraft alternator to the slip ring assembly at a prescribed on/off cycle.

- Return Filters

Return filters are provided at the central reservoir to filter return oil from the pitch change regulator and from the regulator scavenge return from the reduction gearbox.

4.3.2.2 Description of Operation and Safety Features

Pitch change fluid (P_s) is supplied to the pitch change regulator by the variable delivery pump at up to 3000 psi and is routed to the beta valve in the pitch change actuator through a rotating transfer bearing and tube assembly (reference Figure 4.3.2.1.5-1). This supply fluid is also connected to a small electro-hydraulic valve (EHV) in the pitch change regulator. Upon receiving an electrical pitch change voltage signal from the FADEC, the EHV meters fluid to a servo gear motor which rotates an input shaft to the pitch change actuator through a differential gear train.

Rotary shaft motion is converted to linear motion at the beta valve by a pitch lock thread (reference Figure 4.3.2.2-1). As the pitch lock nut thread rotates, it advances or retracts and moves the valve off null. The actuator, which is integral with the screw, then moves returning the nut and valve to null for

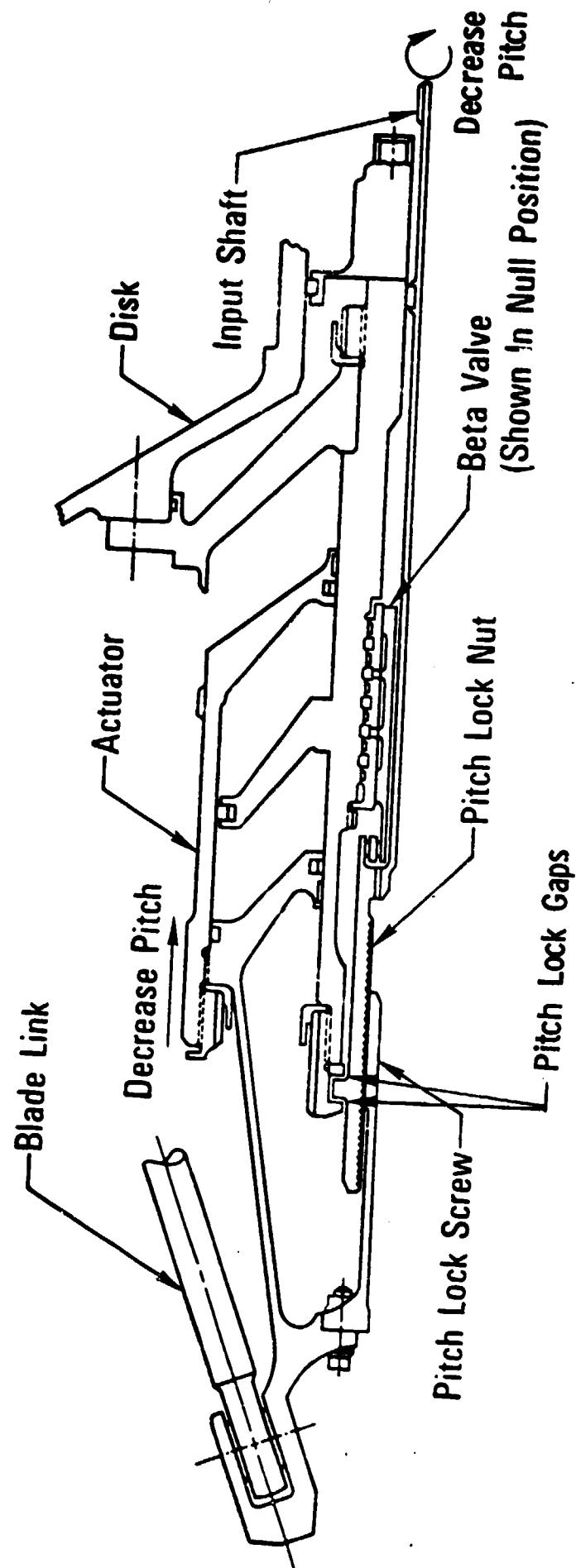


Figure 4.3.2.2-1. Pitch change actuator

automatic mechanical back. The nut position thus remains constant for all actuator positions and is essentially an infinitely adjustable low pitch stop. If hydraulic pressure is lost at any actuator position, pitch lock occurs as a result of blade loads forcing the actuator and the pitch lock nut through a preset gap to ground against the fixed actuator piston. The gap through which the actuator travels to lock pitch from any blade position represents approximately one degree of blade angle motion. The system is sized to provide a maximum pitch rate capability of 30 degrees/second under normal operating conditions. Return fluid flow (P_R) from the pitch change actuator, EHV and servo motor is directed from the pitch change regulator to the central lube oil reservoir through a filter located at the reservoir. Check valves are located in the pitch change regulator supply lines from both the main and auxiliary pumps to prevent back pressurizing one pump from the other.

Blade position feedback to the FADEC is provided by redundant linear variable differential transformers (LVDT) mounted in the pitch change regulator. Since a mechanical drive path exists between the servo motor and the blades via the differential gearing, shaft, pitch lock screw, actuator and blade links and arms, blade angle is a direct function of servo motor revolutions. A gear meshed with the motordriven gear translates a fine-pitch screw to impart linear motion to the LVDT as a function of motor rotation (i.e., blade angle). LVDT output voltage is provided to the FADEC as the indication for blade angle.

During normal operation, supply flow to the EHV and metered flow to the servo motor pass through a feather solenoid valve. Feathering is accomplished by energizing the feather solenoid and the auxiliary pump motor. This bypasses the EHV and directs supply flow directly to the high pitch side of the servo motor. Auxiliary pump flow augments normal pump flow to drive the blades to the feather position as set by an actuator travel stop. The blades are unfeathered by de-energizing the feather solenoid, energizing the auxiliary pump motor and transmitting a low pitch signal from the control to the EHV. The feather solenoid valve has two coils fed by two separate electrical circuits for redundancy. The auxiliary pump motor can also be energized from either of the two circuits to insure the ability to feather when required.

The feathering operation can be commanded by FADEC or by the pilot. An automatic feathering capability can be provided during takeoff such that any malfunction in the Prop-Fan

or power section resulting in a significant loss of thrust will cause the FADEC to command the Prop-Fan to feather.

Regulator gears and bearings are lubricated by transfer bearing leakage flow which then drains to an isolated scavenge sump in the main drive reduction gearbox to be returned to the central lube reservoir through a filter.

4.3.2.3 Weight (lbs)

The weight of the Prop-Fan configured for this study is estimated at 1298 pounds. Previous parametric Prop-Fan weight studies (Reference 5) show that the total weight of this Prop-Fan should be 1225 lbs, not including the weight associated with the disk flange joint. The added disk flange joint represents 20 pounds.

The estimated weights (lbs) of the remotely-mounted components which are not included in the above weight are as follows:

| | |
|----------------------------------|----------|
| Hydraulic Variable Delivery Pump | 15 |
| Auxiliary Pump and Motor | 10 |
| Deicing Timer | <u>1</u> |
| Total Remote Component Weight | 26 |

4.3.2.4 Design Features Relative to Improved Reliability and Maintainability

4.3.2.4.1 Replaceable Assemblies

The Prop-Fan has been designed to permit any subassembly to be quickly replaced on the aircraft or, or to replace the whole assembly if it is more expedient. A discussion of the need for replacement and the procedure to be followed for replacement of subassemblies follows (reference Figures 4.3.2.1-2).

4.3.2.4.1.1 Blades

The primary cause for replacing blades is foreign object damage (FOD) of the blade shell or deicing heater. The blade spar is designed as a primary structure to last the life of the aircraft. Metallic sheet-type heaters will be utilized instead of the wire element heaters currently in use. These heaters are more

tolerant of FOD damage, more erosion-resistant and less susceptible to open soldered joints with lead-in braid than the wire element heaters. If blade replacement is required, the following procedure should be followed:

1. Remove the spinner by unscrewing the single nose attachment bolt.
2. Disconnect four deicer leads at the slip ring assembly and four deicing leads at the forward end of the deicing conduit assembly.
3. Drain blade retention bearing oil.
4. Remove the forward cover from the disk.
5. Detach the link from the blade arm.
6. Place the blade to be removed in a horizontal position and attach a sling and hoist over the blade center of gravity.
7. Remove the exterior blade clamp.
8. Slide the blade in horizontally until it rests on the disk.
9. Remove the blade retention ball complement and retainer inside the disk.
10. The blade can now be removed horizontally from the disk on the hoist.
11. Reverse the procedure to install a blade.

4.3.2.4.1.2 Pitch Change Actuator

The pitch change actuator is designed structurally for the life of the aircraft and should not require replacement except for possible seal maintenance. To replace the actuator, remove the spinner and deicing conduit assembly, drain the blade retention bearing oil and remove the forward cover as for the blade replacement.

1. Detach the eight blade links from the blades.
2. Place a lifting dolly under the actuator and remove its attaching bolts. This allows the actuator to be removed.

3. Quick-disconnect valves seal oil within the actuator for a "dry pull" when the transfer tubes disengage.
4. Reverse the removal procedure for installation.

4.3.2.4.1.3 Transfer Tube Assembly

The transfer tube assembly should not require removal except for possible seal leakage. After removal of the pitch change actuator the transfer tube assembly can be removed forward after removal of the screws attaching the mounting flange to the main drive reduction gear shaft. Reverse the procedure for installation.

4.3.2.4.1.4 Slip Ring Assembly

Brush replacement due to wear is the primary reason for removal of this assembly. Although the small drum-type slip ring significantly reduces wear by reducing brush rubbing velocity (from 4,870 feet per minute for the 54H60 to 785 feet per minute for the Prop-Fan), the brushes will eventually require replacement. To remove this assembly:

1. Disconnect the deicer leads at the rear of the slip ring assembly.
2. Loosen the single tie bolt nut on the coupling clamp, expand the coupling and remove the unit.
3. Reinstall in reverse order.

4.3.2.4.1.5 Pitch Change Regulator

The pitch change regulator may require replacement due to malfunction of the EHV, solenoids, servo motor or LVDT or for excessive transfer bearing or rotating shaft seal leakage. To remove the regulator, remove the slip ring assembly as described above.

1. Disconnect electrical and hydraulic connectors.
2. Loosen the single tie bolt nut on the coupling clamp, expand the coupling and remove the regulator.
3. Reverse the procedure for installation.

The slip ring assembly can remain attached to the regulator for installation and removal of the regulator, if sufficient axial space is available in the nacelle.

4.3.2.4.1.6 Rotor Assembly and Pitch Change Module

The total rotor assembly and pitch change module can be removed as a unit if this is advantageous (e.g., replacement of the gear reduction). Remove the spinner and deicing conduit assembly, drain the blade retention bearing oil and remove the forward cover assembly as for the pitch change module replacement.

1. Attach a lifting fixture and hoist to the forward disk flange.
2. Remove the bolts in the disk mounting flange and remove the unit with the hoist.
3. Reinstall in reverse order.

4.3.2.4.2 Line Balance Requirements

Major Prop-Fan components will be individually balanced to permit line replacement and interchangeability without the need for re-balancing the total assembly. The spinner will be dynamically balanced and the disk and pitch change module will be statically balanced. Blades will be aerodynamically balanced and vertically and horizontally mass balanced against a master blade to the degree required for field replacement without rebalance.

If a service blade being replaced is badly eroded, blades may require replacement in diametrically opposite pairs to allow for the mass difference between old and new blades.

4.3.2.4.3 On-Condition Maintenance

The Prop-Fan design is based upon the concept that no scheduled overhauls are required to achieve on-condition maintenance. Design features that promote on-condition maintenance are as follows:

- O All elastomeric seals are manufactured from non-age controlled materials.

- The blade spar and disk are prime structures designed for the life of the aircraft.
- A method is provided for checking slip ring assembly brush wear. This inspection permits brush replacement at periodic inspections prior to failure.
- Fault detection and isolation using diagnostics to detect problems prior to their reaching critical proportions is provided, as described in paragraph 4.3.2.4.6.

4.3.2.4.4 Spinner Heater Eliminated

Service experience with turboprop spinners indicates that anti-icing heaters are not required. Therefore this feature is not required.

4.3.2.4.5 Line Rigging Requirements

The only items that require line rigging are the pitch change actuator and the pitch change regulator. Tolerances on blades, arms and links are held sufficiently close during manufacture or by initial assembly adjustment to preclude rigging the blades. An actuator rigging fixture will be used to simplify the task of installing either the actuator or regulator.

4.3.2.4.6 Fault Isolation and Diagnostics

A system of fault isolation and diagnostics is used to provide in-flight monitoring of the Prop-Fan, power section, and reduction gearbox condition. This system is an important aid to on-condition maintenance because problems can be detected and recorded for correction before serious malfunctions occur. Prop-Fan inputs to the condition monitoring system are regulator supply pressure and flow, and blade position from the LVDT to monitor pitch change performance. Accelerometers are mounted on the reduction gearbox to monitor the vibration spectrum. Environment One (E1)* analysis of oil returning from the pitch change regulator monitors oil condition. Magnetic plugs also monitor pitch change regulator return oil to detect large metallic particles. Although the power section, main drive reduction gearbox and Prop-Fan use common lubrication oil from a common reservoir, fluid for the systems is isolated during operation for E1 analysis and filtration before return to the reservoir. The only exception is a mixing of rear reduction gear shaft bearing lubrication flow with pitch change regulator lubrication flow in a common scavenge return line. Since these components are in the same location for fault isolation, it was desirable to eliminate a rotating shaft seal between them for improved reliability.

* Environment/One's (E1) Oil Condition Monitor is an in-line lubrication system monitor designed for the continuous detection and trending of abnormal conditions of oil-wetted components.

4.3.3 Main Drive Reduction Gearbox

4.3.3.1 Development of Power Train Arrangement

Two basic reduction gear power train arrangements were investigated in some depth. First was an updated increased power version of a 501 gearbox arrangement - an offset planetary as shown in Figure 4.3.3.1-1. Second was a dual compound idler configuration that was proposed for future high life applications, shown in Figure 4.3.3.1-2.

The offset planetary design initially conformed to current DDA practices regarding bearing selection and produced a power train bearing set life of approximately 8000 hours (AFBMA L10)*. The reliability data analysis and preparation of the requirements for the advanced system, specifically the definition of bearing set life for the anticipated applications, revealed the need for much greater reliability. Therefore a second generation sketch was made, Figure 4.3.3.1-3. A size increase resulted, particularly in the planet system where larger planet bearings required bigger planet and ring gears. The bearing set life was increased to 35000 hours (AFBMA L5.7)**. This bearing life increase resulted in an approximate 130 pound weight increase - about 21 percent of the basic power train plus housing weight. A change from magnesium to aluminum housings was also made at a weight increase of about 100 pounds.

The dual compound idler gearbox was also designed to a bearing set life of 35,000 hours (AFBMA L5.7). The initial design was found to have too great a centerline offset - vertical distance from propeller shaft to power section centerline - to fit into the nacelle diameter required to blend properly with the propeller spinner. A second generation design with increased first stage ratio and finer pitch gears was made as shown in Figure 4.3.1-2.

These second generation designs provided a common baseline for preliminary direct cost and weight comparisons between the two power train arrangements as shown in Table 4.3.3.1-I. The dual compound idler design is somewhat heavier but has fewer parts and costs less. The new arrangement is considered sufficiently competitive to warrant continued evaluation hence it was chosen for use in the projected turboprop propulsion system.

*Anti-Friction Bearing Manufacturers Association rated life for 90% reliability.

**AFBMA rated life for 94.3% reliability. (Approximately equivalent to 50,000 hrs L10 initial design goal.)

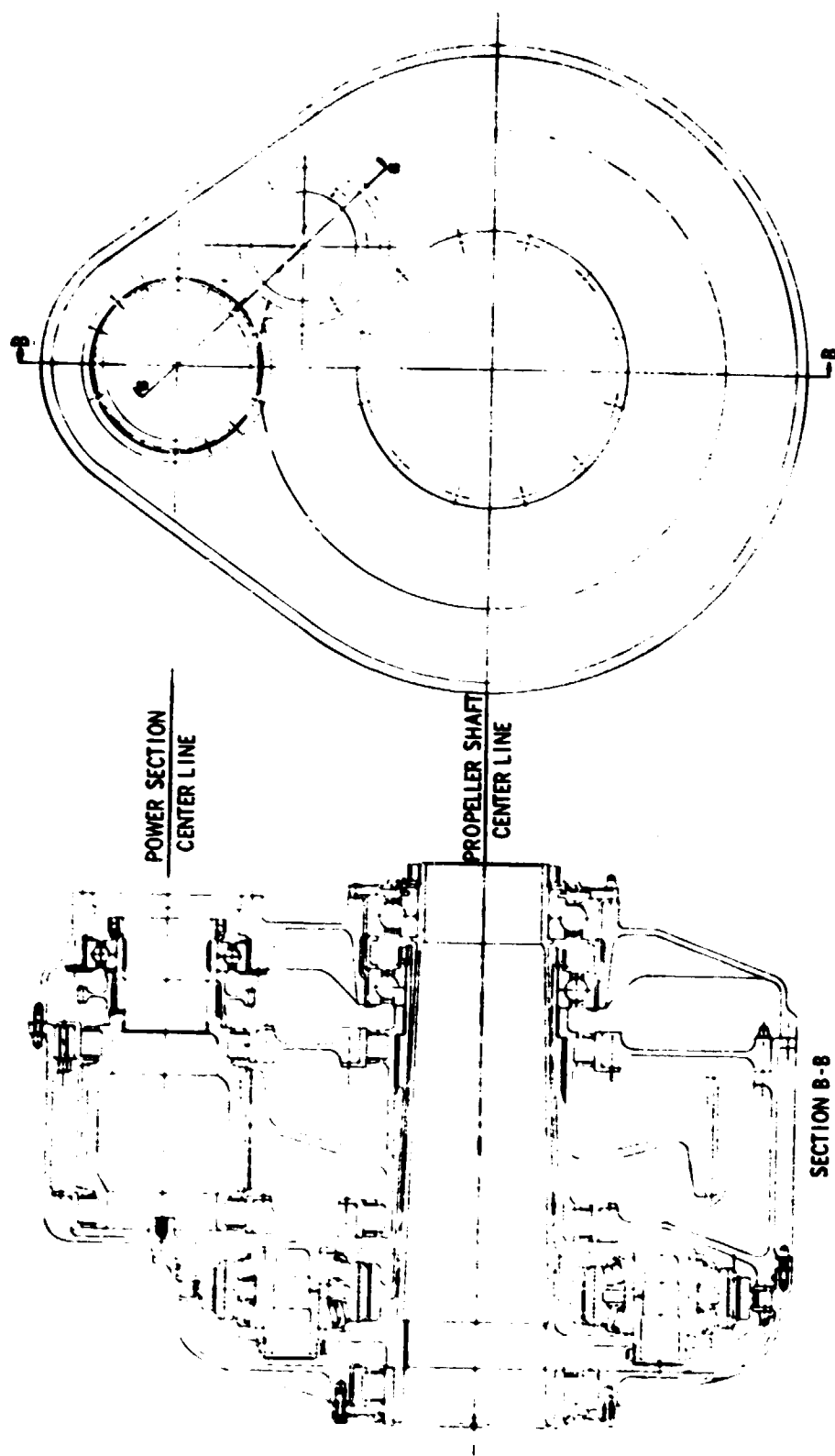


Figure 4.3.3.1-1. Basic offset planetary gearbox powertrain

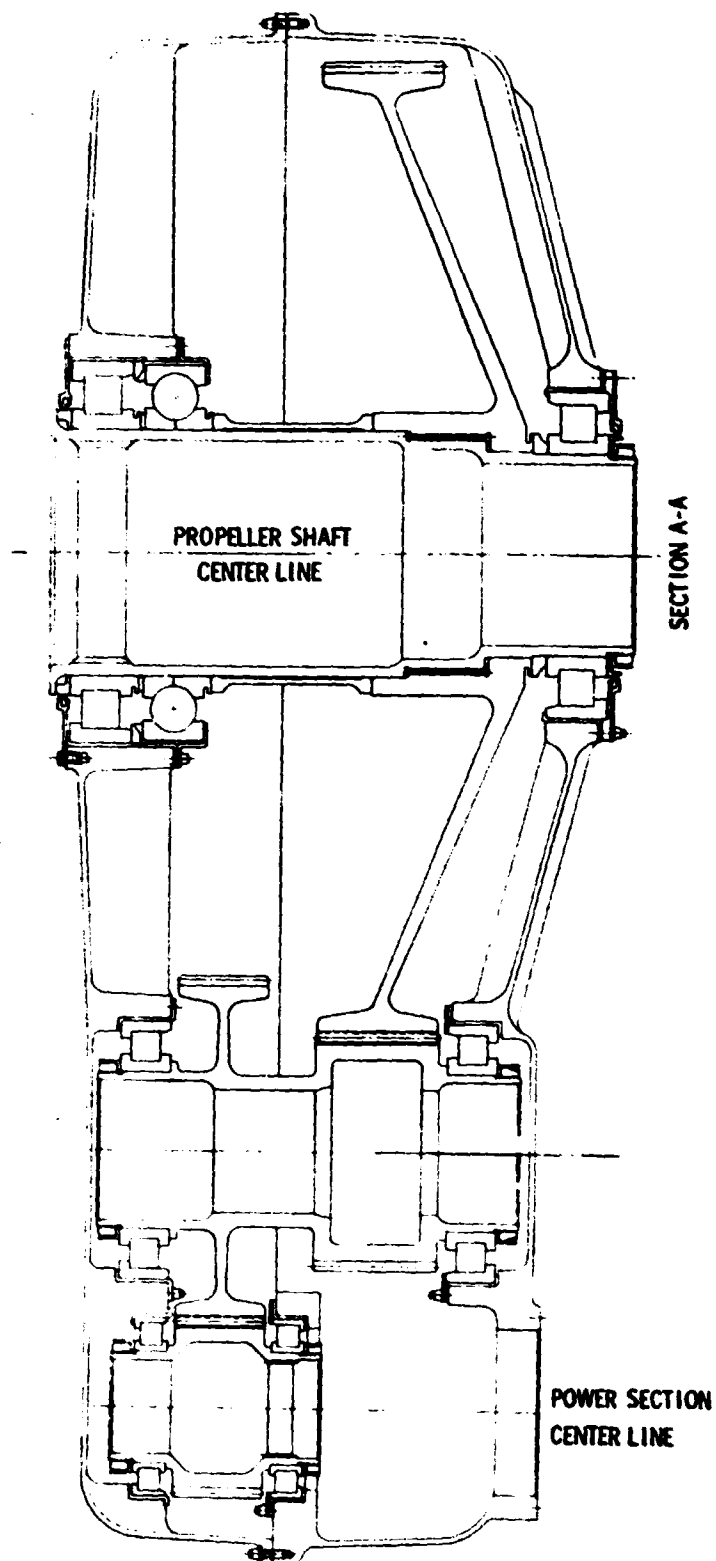


Figure 4.3.3.1-2. Basic dual compound idler gearbox powertrain.

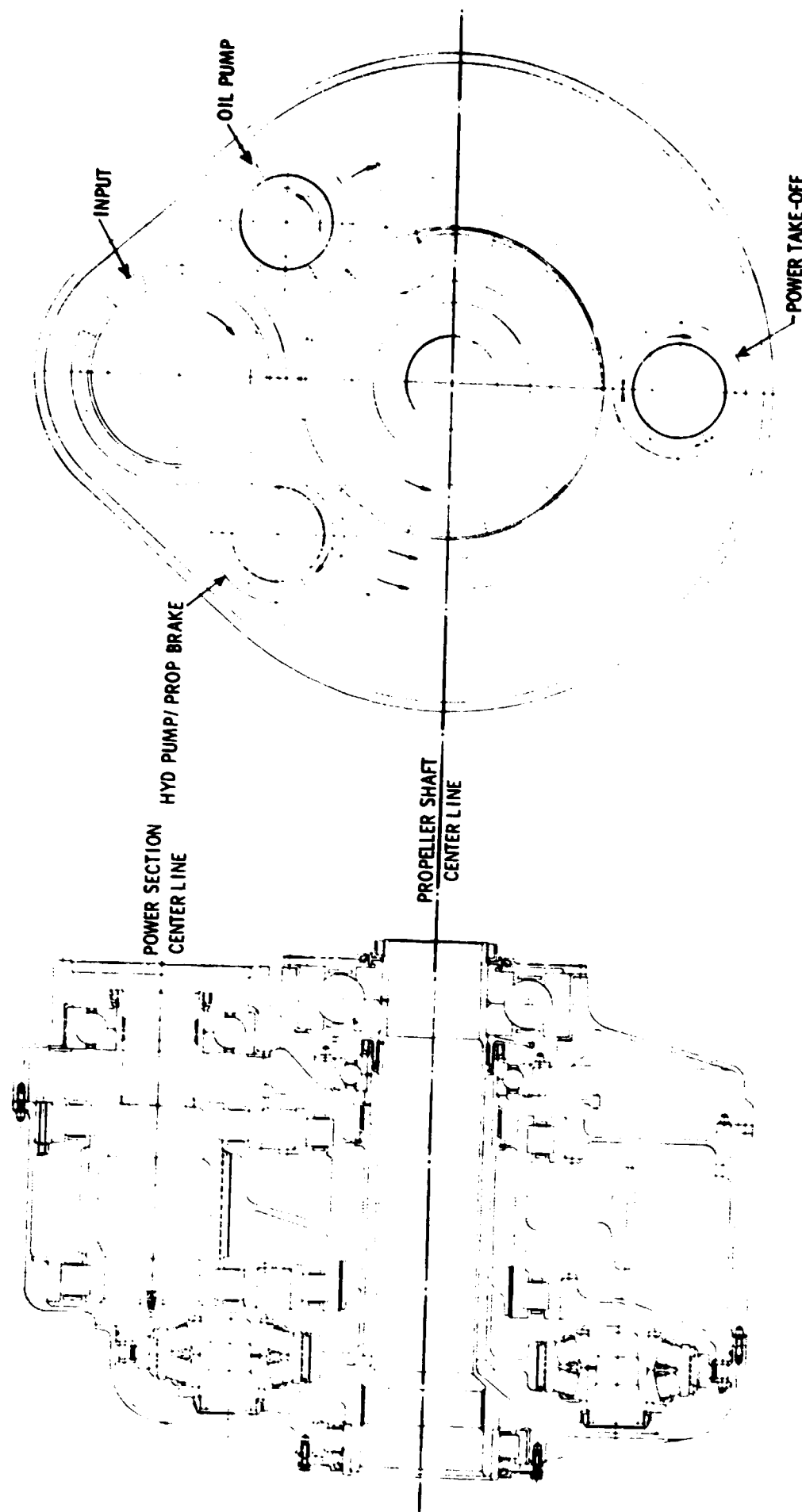


Figure 4.3.3.1-3. Offset planetary powertrain with high life bearings.

In the dual compound idler arrangement the only question is with respect to achievement of equal loading between the two idlers. It is believed that this can be satisfactorily resolved during an actual design and development program.

TABLE 4.3.3.1-I

Comparison of Offset Planetary and Dual Compound Idler Gearboxes

| <u>Characteristics</u> | <u>Offset Planetary</u> | <u>Dual Compound Idler</u> |
|------------------------|-------------------------|----------------------------|
| Relative Cost | 100% | 63% |
| Weight | 837 lbs. | 887 lbs. |
| Power Train Gears | 11 | 6 |
| Power Train Bearings | 22 | 10 |
| Total Part Numbers | 275 | 260 |

4.3.3.2 General Description

The reduction gearbox power train is a two stage dual compound idler type as shown in Figures 4.3.1-2 and 4.3.3.2-1. Two tubular struts and an extension shaft housing structurally attach the gearbox to the power section. The LP rotor drives an extension shaft that attaches to the gearbox input pinion. The input pinion drives two idler gears for the first reduction stage. Each of these idler gears are integral with a coaxial pinion that together drive a single gear mounted on the propeller shaft for the second reduction stage. The first and second stage reductions are 2.5 and 3.37 respectively for a total reduction of 8.4 overall. All the power train gears are helical. The helix angles of the two reduction stages are chosen to balance the axial thrusts developed by the two gears comprising each compound idler alleviating any need for a thrust bearing on each idler. The input pinion helical gear thrust is carried by a split inner race ball bearing. The propeller shaft gear helical thrust opposes the propeller thrust (during normal flight operation) with the resultant carried by a split inner race ball bearing.

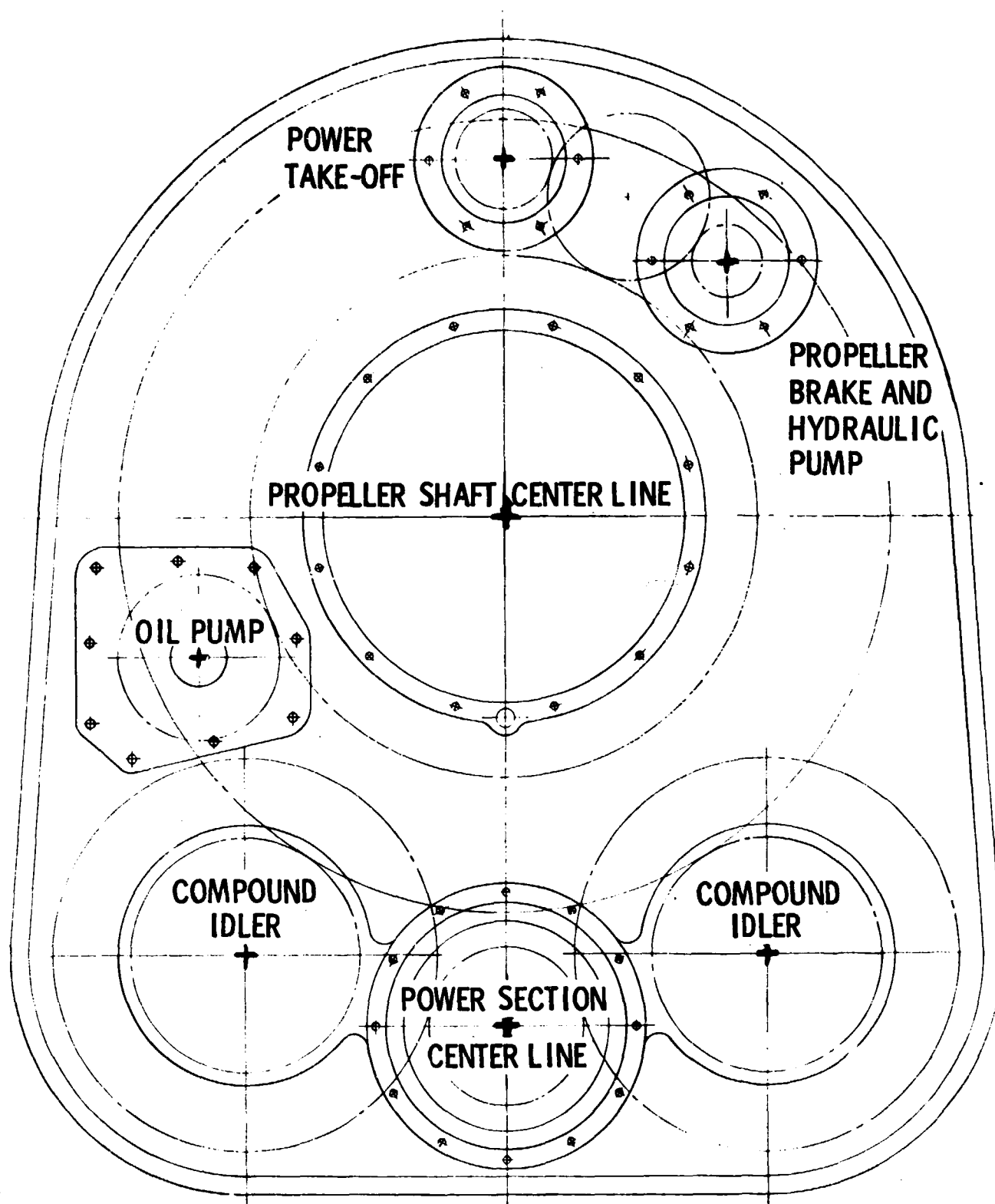


Figure 4.3.3.2-1. Rear view of compound idler reduction gearbox.

Both ball bearings are loose fit on their O.D. so they support no radial loads. The input pinion, the two compound idlers, and the propeller shaft are each supported by a cylindrical roller bearing at each end. These roller bearings carry the helical gear tangential, separating and thrust moment loads. The propeller shaft roller bearings also carry the propeller radial and moment loads.

The accessory drive system is limited to three drive pads on the rear face of the unit. An oil pump, hydraulic pump and power take-off drive are provided.

The power take-off is intended to drive a remotely (aircraft nacelle) mounted aircraft accessory drive gearbox. A constant speed drive alternator/generator, hydraulic pump(s) and EDC/cabin supercharger drive pads would typically be incorporated on such a gearbox.

The accessory drive train consists of four gears driven by a single gear mounted on the propeller shaft. All gears are spur type center mounted on cylindrical roller bearings.

4.3.3.3 Design Rationale

4.3.3.3.1 Gears

Helical gears were chosen over spur gears to provide quieter operation with less vibration. Fretting of contacting surfaces throughout the gearbox and attached accessories should be significantly reduced. Also fatigue of fasteners and any overhung mounted part should be reduced. As a result, fewer premature removals from failures initiated from fretted areas or from resonant vibration induced cracks will occur. Less expense will be incurred at overhaul to repair and/or replace parts with fretting or vibration fatigue cracks. Fewer spare parts will be required minimizing capital investment.

The required overall reduction gear ratio was set by the power section LP rotor speed and the propeller speed necessary to obtain the desired performance from each of these major modules. The split between the first and second reduction stage ratios is a design variable determined by the optimization that results in each application by the relative importance attached to overall size, length, weight and individual gear and bearing loads and lives.

In the present application a first stage ratio between 2.0 and 2.5 appears to be required. Larger ratios tend to be heavier

and to be so broad horizontally across the idler gears that they do not fit into the round nacelle section desired in such close proximity to the propeller spinner.

The gear design limits that were used were the current DDA values of:

| | |
|---------------------|------------------------|
| Contact Stress | 160,000 psi |
| Bending Stress | 40,000 psi |
| Pitch Line Velocity | 25,000 feet per minute |

The design shown uses the same (seven) diametral pitch gears in both stages. The first stage gear face width is determined by the contact stress limit while the bending stress limit determines the second stage gears. Refinements during the detail design process would likely revise the gear design parameters slightly to more nearly balance these limits in the final configuration.

Gear tooth alignment must be better than normal due to the wide face width of these gears. Methods to achieve the best possible alignment must be investigated and incorporated into the finalized design to assure long life operation. Offsetting the bearing bores in the housings will likely be necessary to compensate for the difference between front and rear bearing load directions on the two compound idlers. Appropriate matching of idler gear bearing annular thickness will improve alignment and help preserve the benefits of bearing bore offsetting. The wide spacing of the idler bearings will be helpful as will the location of the second stage reduction gear at the center of the propeller shaft bearing span where angular deflection will be a minimum.

Gear tooth windup from torque will be considered and compensated for in the final design by use of finite element programs to determine optimum gear blank proportions. Initial radial deflection matching has been provided by utilizing center webbed gears and bottle bored pinions. Further matching will be achieved by use of rim thicknesses inversely proportional to pitch diameter. Control of radial deflection is believed required since such displacements of the tooth profile result in poor contact patterns and possible effective misalignments.

Equalization of the load carried by the two idler gears is of course essential to successful operation. A number of manufacturing and assembly procedures can be used to assist in achieving equal loading, but the development of a mechanical load sharing

device will probably be necessary. Synchronized gear tooth meshing should help match bending deflections.

4.3.3.3.2 Bearings

Non-integral races were chosen for all power train bearings to maximize fatigue life by permitting the specification of M50 or other through-hardened materials not suitable for gears. Material processing such as controlled grain flow is also practical on bearing rings but would be very difficult on less symmetrical part configurations such as the idler gears and propeller shaft. A life improvement factor of twenty was used for M50 chemistry, VIMVAR melted and controlled grain flow forged steel. Carburizing gear material VIMVAR melted in comparison might have a life improvement factor of only six. Maximization of bearing life means that smaller, lighter weight, bearing envelope sizes would be used. The dynamic operating characteristics of the smaller bearing would be better, particularly for the high speed input pinion ball and roller bearings. The idler and propeller shaft bearings are slow speed applications for which tapered roller bearings may be considered. Tapered bearing races are not likely to be considered by the manufacturing departments for integration onto gearbox parts.

The preliminary layouts used bearing envelope sizes based on AFBMA calculations. Envelope size was selected to produce the desired bearing set reliability. These bearing sizes should be fairly representative of a finalized design in all but the input pinion bearings where some adjustment may be necessary due to the rolling element centrifugal force loads for the moderately high shaft speed (9545 rpm). The first and second stage gear helix angle of about 10 and 3.5 degrees respectively were chosen to provide the least thrust load possible on the input pinion ball bearing while still maintaining helical gear overlap greater than one.

4.3.3.3.3 Propeller Shaft Offset

Propeller shaft offset direction and amount is determined to a large extent by the application. The current anticipated applications prefer the propeller shaft above the power section axis. The propeller spinner diameter set the maximum offset since the reduction gearbox is located immediately aft of the spinner. An offset close to the maximum was desired to prevent impingement of the power section exhaust against the underside of the wing (or to eliminate the necessity to deflect the exhaust away from the wing).

The dual compound idler type power train is unique in that the amount of offset can be varied somewhat without changing any of the gears. The input pinion can be moved vertically and the idler centers adjusted appropriately. Housings with new support bearing centers would be required. The projected gearbox input pinion is located approximately on a level with the two idler centers. This results in nearly equal and opposed pinion bearing load components from the two tangential gear forces. Since the input pinion is the highest speed power train part this low load contributes greatly to long bearing life.

A higher pinion position (as above the idler centerline) would improve the vector sum of the right hand idler gear forces but the resultant load directions for the front and rear bearings would likely be more disparate hence alignment and dynamic performance might suffer. Also such a position would require additional gearbox length to permit location of a pinion bearing between the two reduction gear stages. This position would reduce center distance much more than desired in the projected design applications.

4.3.3.3.4 Housings

Aluminum housings were used in the weight comparisons. Either aluminum or magnesium could be used in a final design. The higher horsepower rating of the advanced engine compared to the 501-D13 suggest such increased loads relative to housing size that the higher modulus of aluminum may produce the lightest weight design.

4.3.3.4 Design Optimizations Required

The reduction gear design projected herein is not a completely engineered design. A number of studies are still required to verify some of the design choices noted in the previous sections. Chief among these studies are:

- Analysis of integral vs. non-integral inner race and flanged vs. non-flanged outer race bearing designs based on life-weight-cost considerations. This can best be accomplished by utilizing the DDA DOC computer program and/or value engineering department analysis.
- Design and analysis of mechanisms for insuring equal load sharing between the two idler gears. One

possible scheme is the use of tapered roller bearings and mismatched helix angles for the two gears on each idler. The slight thrust load difference thus produced would be balanced by a hydraulic piston located co-axial with each idler in contact with the bearing outer race. A valve attached to the piston would control the pressure oil supply into the piston to increase piston pressure as needed to balance the thrust load. Interconnecting the pistons for the two idlers would cause one idler to slightly shift axial positioning to balance the thrust loads on the two idlers. This scheme is sketched in Figure 4.3.3.4-1.

- Analysis of gear and bearing loads to select optimum first/second stage reduction ratio split and axial location (first stage toward front or toward rear of gearbox) and propeller shaft bearing spacing. Helix angle optimization and center distance should also be included. This study can be best accomplished by writing a computer program based on the general gear arrangement to calculate the operating loads, select bearings, and calculate weights; then vary the ratios, helix angles, bearing spacing, etc., until an optimum is determined.
- Analysis of gear tooth surface fatigue life based on Reference 6 should be made and reported. DDA experience to date should be reviewed in depth to assure that current crushing stress design limits are adequate for the long life expected from this advanced propulsion system.

4.3.3.5 Auxiliary Functions

There are three areas of design simplification over current operating turboprop systems.

4.3.3.5.1 Accessorized Propeller Brake

The 501-D13 engine incorporates a propeller brake integrated into the reduction gearbox accessory drive train. The advanced turboprop design study projects a requirement for a propeller brake by some airline operators. The brake would prevent windmilling propeller blades on parked airplanes (when windmilling torque from

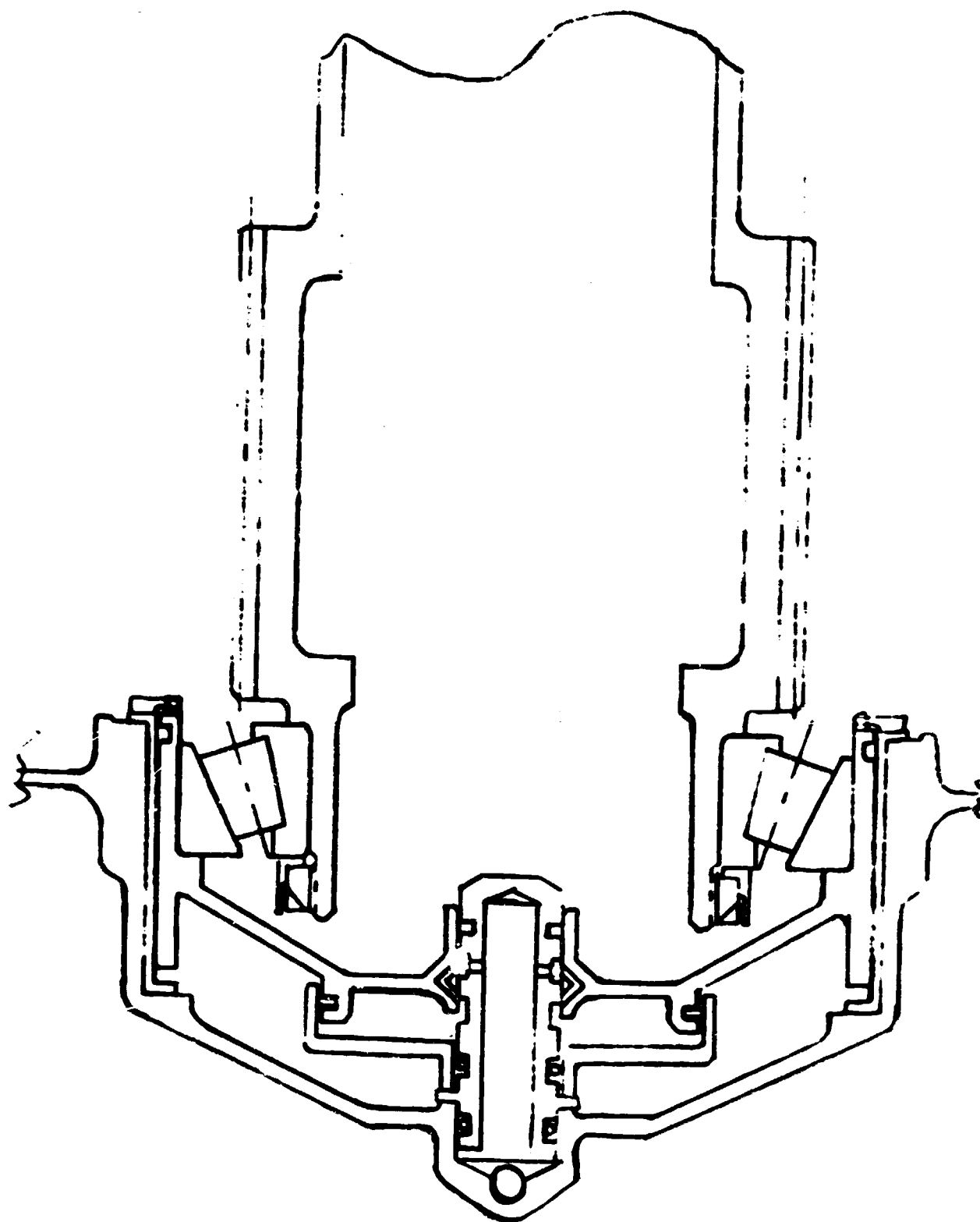


Figure 4.3.3.4-1. Idler equal load sharing design.

ground winds exceeds engine and accessory drag torque). The brake also decreases the time required to stop the propeller after engine shutdown thus expediting passenger deplaning. However, it adds some complexity and associated maintenance costs.

A propeller brake packaged as an accessory for optional use is therefore provided as shown in Figure 4.3.3.5.1-1. In event of excessive slippage or failure to disengage, the unit could be quickly replaced on the flight line. The accessorized brake would have all the features of the current 501-D13 design except that since it is no longer co-axial with the starter, additional control system tie-ins to effect release, such as for starting, would be required.

To reduce the number of accessory drive gears contained within the main drive reduction gearbox the propeller control hydraulic pump is mounted piggy-back on the propeller brake. The speeds and sizes of these two accessories are sufficiently compatible that such an arrangement appears feasible.

4.3.3.5.2 Torquemeter and Safety Coupling

No 501-D13 type mechanical torquemeter function is considered necessary for the projected propulsion system. The condition monitoring sensors and the electronic control system will provide operating data to permit automatic computer calculation of propulsion system thrust and torque for comparison with aircraft requirements and for torque limiting for reduction gearbox protection, and for auto-feather.

An extension shaft and housing replaces the torquemeter. This housing pierces the power section inlet air stream and will therefore be supplied with sheet metal covers to which anti-icing air can be supplied. Anti-iced areas of the projected power section will likely be the same as existing on the present 501-D13 engine.

The 501-D13 engine includes a safety coupling that connects the torquemeter to the gearbox input pinion. This coupling contains helical splines that transmit torque in the normal drive direction and immediately separate in event of negative torque above a predetermined value (equivalent to about 1000-1400 horsepower). Such torques may be generated in a single spool engine by a failed

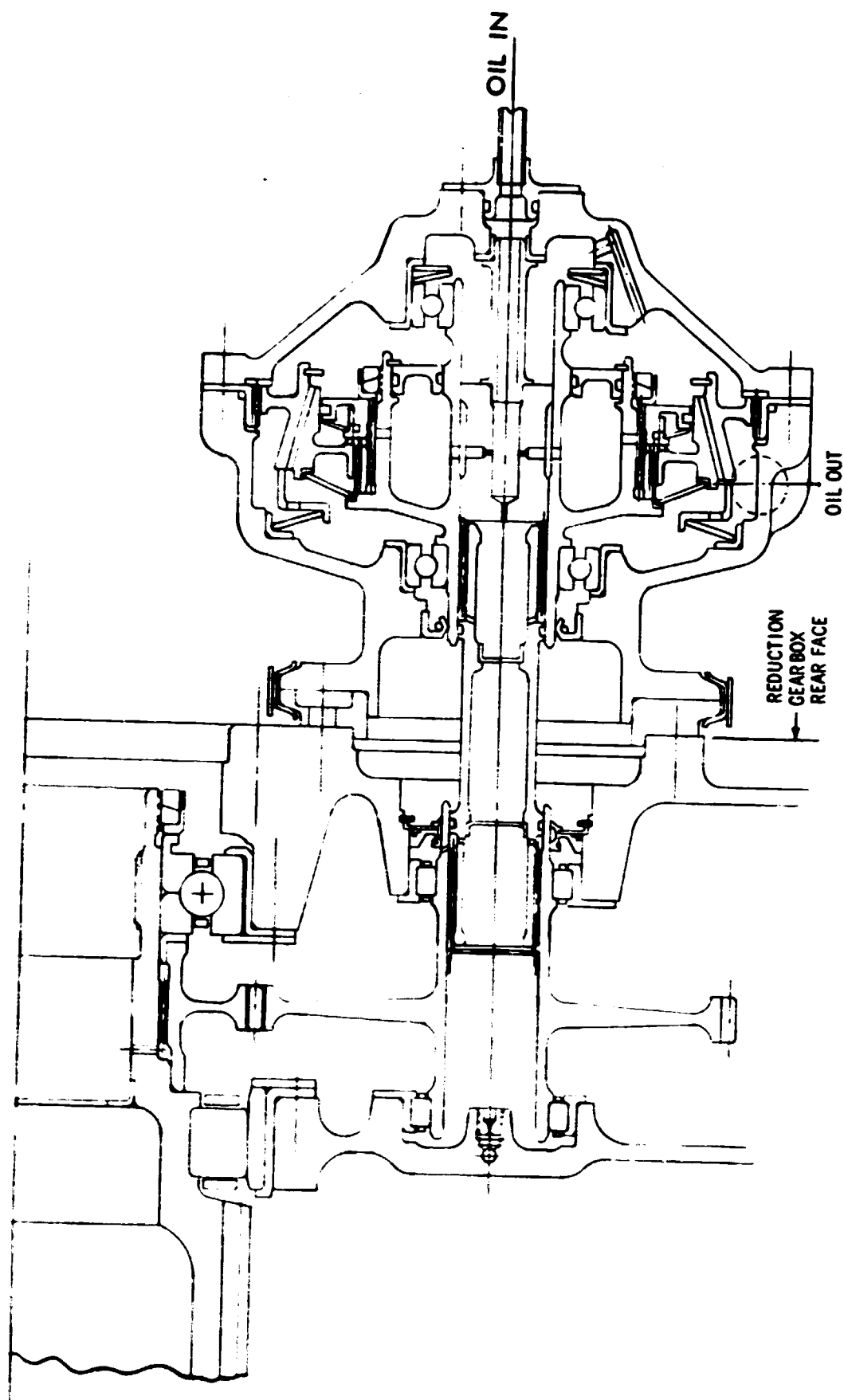


Figure 4.3.3.5.1-1. Accessorized propeller brake.

power section, sudden fuel shut-off, propeller malfunction, etc. These events can cause high negative propeller thrust. The propeller and compressor of the advanced two spool engine are gas coupled hence are not capable of generating such high negative torque at the propeller in similar circumstances. Therefore no safety coupling function is considered necessary and is not included in the advanced design.

4.3.3.5.3 Negative Torque Signal (NTS) and Thrust Sensitive Signal (TSS)

Two control type functions included in the 501-D13 reduction gear assembly are the NTS and TSS systems.

The NTS function senses negative torques and activates a switch at a predetermined horsepower which is much less than required to decouple the safety coupling. The switch may be used to increase propeller pitch as necessary to limit negative torque when engine operating conditions similar to the following are encountered:

- Temporary fuel interruptions
- Air gust loads on the propeller
- Rapid descents in which the power section would be idling and the propeller would tend to overspeed.

Similarly the TSS function senses propeller thrust and provides a signal to auto-feather during take-off whenever thrust is less than a minimum amount. The signal may be displayed in the pilot compartment or provided to the propeller or engine control systems.

As in the case of the safety coupling and torquemeter, the NTS and TSS functions are not required for the advanced turboprop. Torque and thrust indication for previously discussed requirements in the advanced system are provided within the control system by analysis of signals from the engine condition monitoring sensors.

In summary, the projected reduction gearbox is expected to be appreciably simpler than that of the 501-D13 due to the elimination of the need for a number of auxiliary functions. The number of parts required in the 501-D13 gearbox for each of these functions is shown in Table 4.3.3.5-I. The reduced number of parts can be expected to improve the reliability of this module, and to lower initial and overhaul parts and labor costs.

Table 4.3.3.5-I

Elimination of Gearbox Parts Required for 501-D13 Auxillary
Functions And Not Required for Advanced Turboprop

| <u>Function</u> | <u>Part Numbers Required</u> | <u>Pieces Required</u> |
|-----------------|------------------------------|------------------------|
| Propeller brake | 15 | 43 |
| Safety coupling | 15 | 18 |
| Torquemeter | 14 | 17 |
| NTS | 10 | 44 |
| TSS | 14 | 16 |
| TOTAL | 68 | 138 |

4.3.3.6 Accessory Drive Train

The advanced reduction gearbox design contains only five gears and eight bearings within the gearbox for accessory drives. In comparison, the 501-D13 gearbox contains twenty gears and twenty one bearings. Thus the number of gears is reduced 75% and the number of bearings is reduced 61% which will substantially increase gearbox reliability. The 501-D13 and advanced reduction gearbox accessory drive trains are shown in Figures 4.3.3.6-1 and -2 respectively. A comparison of accessory and/or accessory drive provisions and locations in the advanced turboprop is compared with that in the 501-D13 turboprop in Table 4.3.3.6-I.

The reduction in gearbox accessory drive train parts was achieved by elimination of two tachometer drives by utilizing electrical pickup signals from LP and HP rotor toothed parts. The scavenge pumps will be integrated into the pressure oil pump assembly. The starter was relocated to the power section accessory drive train which is in a separate module. The alternator/generator, aircraft hydraulic pump and cabin supercharger have been combined into an aircraft mounted accessory drive train contained in a new separate module driven by a single gearbox power takeoff drive. The size of the remaining accessory gearbox drive train bearings will be selected so that the bearing set life will exceed the reliability requirements. Therefore few accessory drive train failures are predicted.

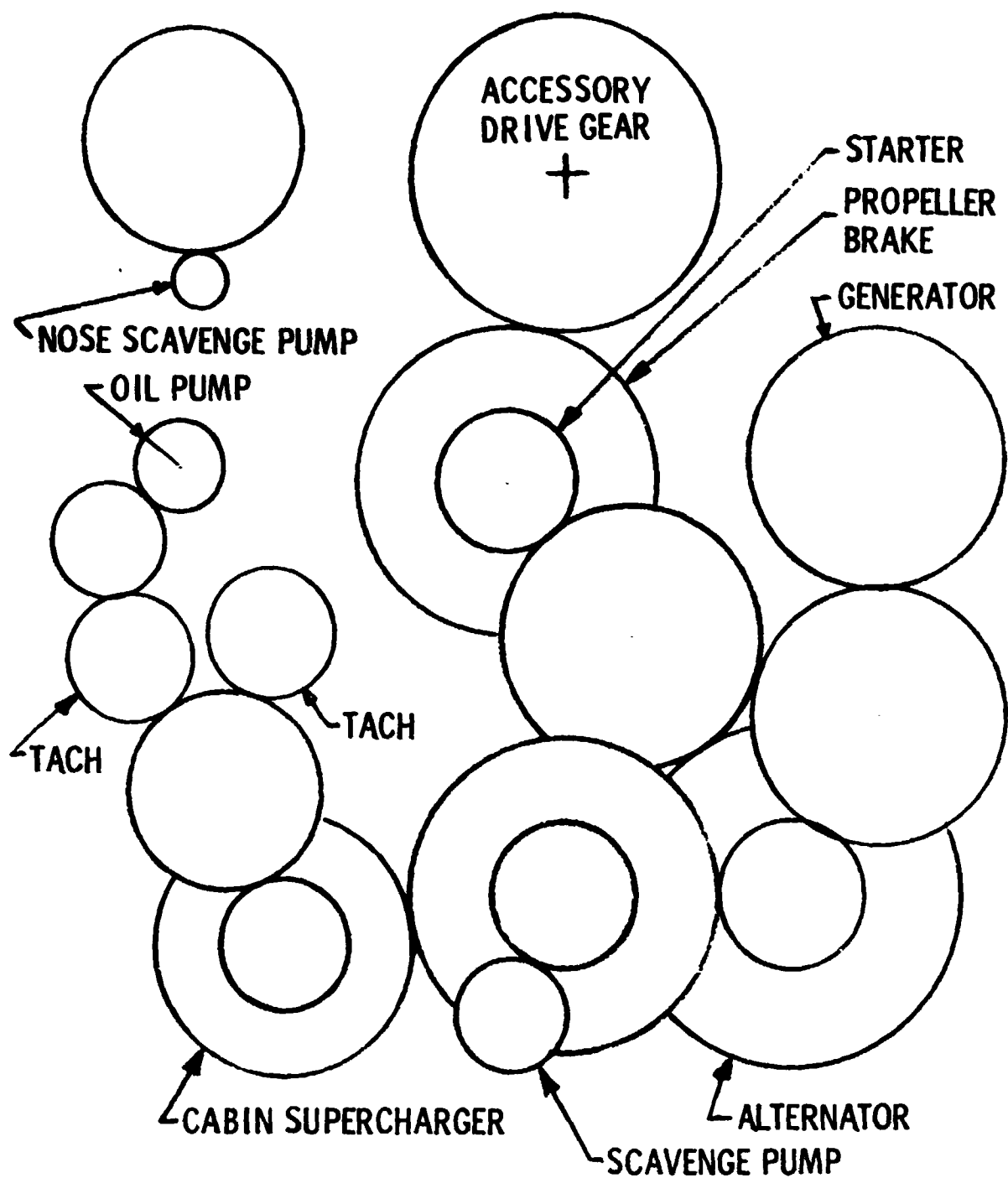


Figure 4.3.3.6-1. 501-D13 reduction gearbox accessory drive train.

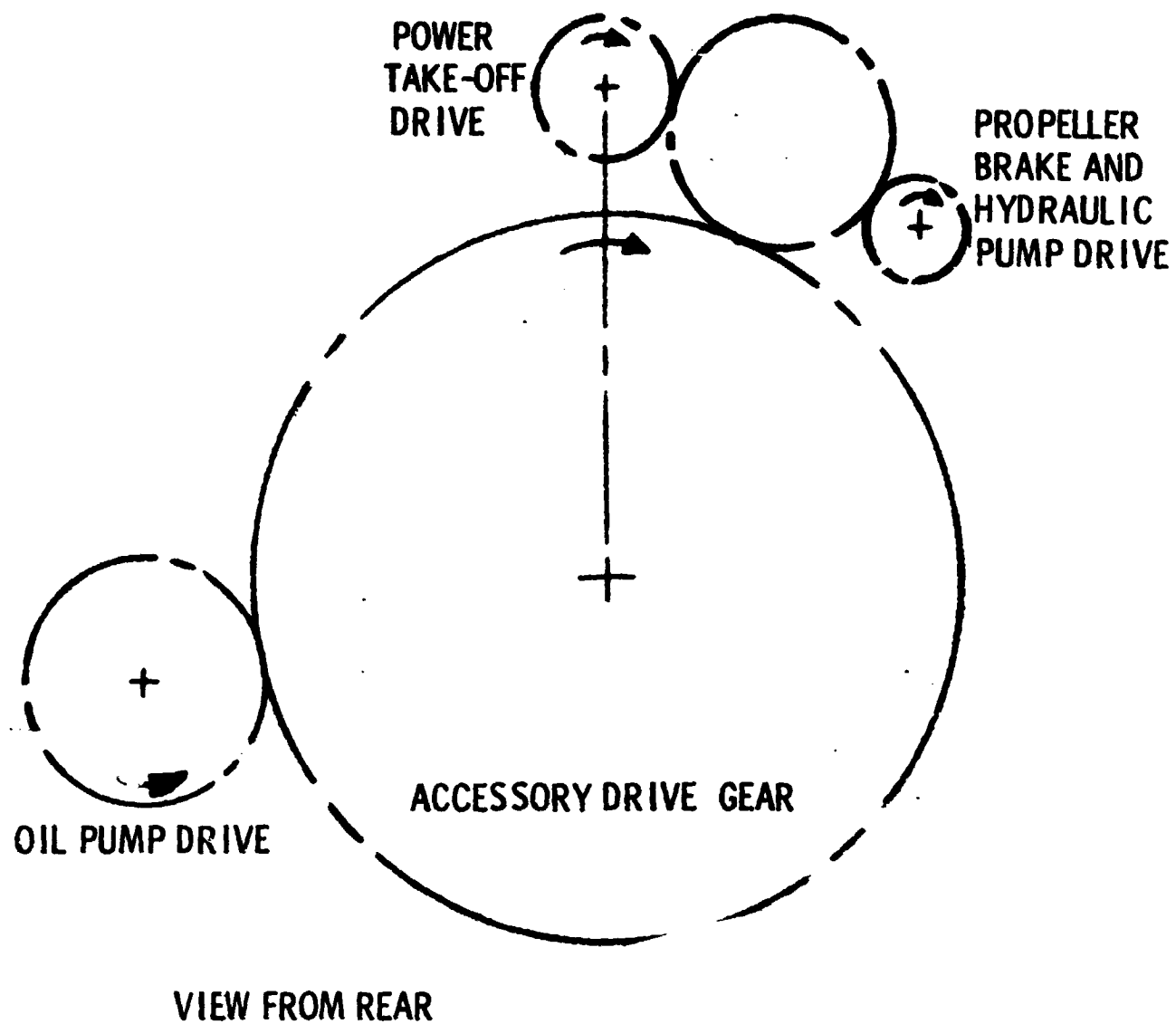


Figure 4.3.3.6-2. Advanced reduction gearbox accessory drive train.

Table 4.3.3.6-I

Comparison of Accessory Drive Provisions and Locations

| | 501-D13 | | | Advanced Turboprop | | | |
|--------------------------------|-----------|-------------------|---------------------------------|--------------------|-------------------|---------------------------------|----------------------------|
| | Propeller | Reduction Gearbox | Power Section Accessory Gearbox | Advanced Propeller | Reduction Gearbox | Power Section Accessory Gearbox | Aircraft Accessory Gearbox |
| Hydraulic Pump (Propeller) | ● | | | | ● | | |
| Propeller Brake | | ● | | | ● | | |
| Starter | | ● | | | | ● | |
| Alternator/Cabin Supercharger | | ● | | | | | ● |
| Hydraulic Pump | | ● | | | | | ● |
| Generator/Hydraulic Pump | | ● | | | | | ● |
| Tachometer | | ● | | | eliminated | | |
| Propeller Alternator | | ● | | | eliminated | | |
| Internal Scavenge Oil Pump | | ● (2) | | | eliminated | | |
| Pressure Oil Pump | | ● | | | ● | | |
| Scavenge Oil Pump (External) | | --- | | | ● | | |
| Aircraft Accessory Pwr Takeoff | | --- | | | ● | | |
| Speed Switch | | | ● | | | eliminated | |
| Speed Valve | | | ● | | | eliminated | |
| Internal Scavenge Oil Pump | | | ● | | | eliminated | |
| Pressure Oil Pump | | | ● | | | ● | |
| Scavenge Oil Pump (External) | | | ● | | | ● | |
| Fuel Pump | | | ● | | | ● | |
| Fuel Control | | | ● | | | ● | |
| Magneto Power Supply | | | --- | | | ● | |
| Centrifugal Breather | | | --- | | | ● | |

(a) - Optional

Items connected with brackets combined in one drive providing increased simplification.

All the projected accessory drive gears will be straddle-mounted on their support bearings, there will be no compound gears (two gears on one shaft) and all but the accessory drive takeoff gear will be integral with its support shaft. The takeoff gear will be located with a tight pilot and driven by a curvic [®] coupling.

These features will provide better gear and bearing alignment and concentricity than was achieved in the 501-D13 accessory drive train. Improved gear meshing and minimum fretting and wear will result in prevention of unscheduled overhauls.

Accessory drive train vibration fretting and wear problems are also partially caused by the torsional load and vibration characteristics of the particular accessories mounted on, and driven by, the drive. These characteristics are seldom included in drive pad specifications (such as MS3329) or even in the accessory manufacturer's catalogs. Some accessory drive train problems may be expected with each new application that uses different accessories and/or accessory operating conditions. The accessory drive train gears are checked during the detail design stage for resonant vibration frequencies that coincide with possible exciting gear meshing frequencies (and the gear design changed if necessary). Exciting frequencies from within the accessory are unknown and cannot therefore be checked. With the variety of accessories generally available for a given functional requirement, the possibility of all operating on a given accessory drive unit without any problem appears relatively small. A possible solution to this problem is the use of a standard set of accessories for all applications.

Accessory weight and overhung moments can change housing resonant frequencies into the range of some propulsion system or accessory excitation frequency. Such occurrence cannot be accurately predicted. Again the use of a standard set of accessories for all propulsion system applications would minimize the possibility of failures and subsequent development costs. Such a policy would permit sufficient propulsion system testing to be conducted with actual accessories to discover and correct any resonant frequency problems during normal development testing rather than after engine certification testing and initial aircraft installations. Since the higher powered accessories are those required by the aircraft and since these will now be remotely mounted, no reduction gearbox housing resonant problems should occur. Also torsional vibrations should be damped out by the power takeoff drive shaft connecting the gearbox drive pad and the remote mounted aircraft accessory drive module.

4.3.3.7 Reliability and Maintainability Improvement

The reliability improvement and assessment of the advanced reduction gearbox is discussed in detail in Section 4.3.9.

Maintainability of the reduction gearbox has been greatly improved primarily due to removal of the aircraft accessory drives to a separate module which can be more easily removed and repaired. In addition the optional propeller brake is designed as a separate accessory and mounted on a standard drive pad so that it also can be removed and repaired without disturbing the gearbox. The scavenger oil pumps will also be externally removable as is the pressure pump. The propeller brake and oil pumps are the mechanisms where some wear over long operating times may be most expected. The remaining wear items are the various shaft seals which are also externally removable. Many maintainability features are small details normally specified during the final detail drawing processes. DDA standard procedures recognize the great importance of such details and provide for both maintainability and value engineering inputs during this phase of an engine design.

4.3.4 Power Section

The advanced turboprop power section, accessory system, and main drive reduction gearbox has significantly fewer parts than the 501-D13. A comparison is shown in Table 4.3.4-I which shows that the advanced turboprop engine has 20% fewer parts. This difference stems from advanced technology in the power section, elimination of the mechanical torque-meter as well as the different design approach in the reduction gearbox. It should be recognized that although the two power sections are approximately the same physical size, the advanced turboprop produces about 2 1/2 times the power output of the 501-D13, with considerably fewer parts. These differences are emphasized further by a comparison of the number of airfoils in the two power stations, as shown on Table 4.3.4-II. The advanced turboprop compressor produces 2 1/2 times the compression ratio with approximately 8% fewer blades, in 15% fewer stages. Conversely, if a 25:1 compression ratio compressor was to be built using the 501-D13 technology level, approximately 500 to 600 more compressor blades would be required. The advanced turboprop turbine stages extract 2 1/2 times the power, with only a 10% increase in the number of blades.

The significance of these comparisons becomes evident when considering the cost of refurbishing an engine which has had extensive airfoil damage such as a result of FOD.

Table 4.3.4-I

Total Number of Parts Comparison

| <u>Model</u> | <u>Power Section</u> | <u>Gearbox</u> | <u>Torque- meter</u> | <u>Standard Parts</u> | <u>Total</u> |
|-----------------------|--------------------------|----------------|--------------------------|---------------------------|--------------|
| 501-D13 | 1105 | 350 | 78 | 346 | 1879 |
| Advanced Turboprop | 857 | 260 | -- | 377 | 1494 |

As shown on Table 4.3.4-I, the number of standard parts on the advanced turboprop have increased by 10%, and this is one area of the power section which would appear to benefit from further study. It is felt that the number of standard parts could be reduced, if a study was made to standardize such things as bolt diameter, head style, material, and lengths; nut type, size, and material; O-ring material and sizes; etc. This would reduce the number of tools required, the cost and size of overhaul/repair parts inventories, and minimize overhaul/repair time requirements.

TABLE 4.3.4-II
Blade Quantity Comparison

| Stage No. | Compressor Blades | | Turbine Blades | |
|-----------|-------------------------|-----------------------------------|----------------|--------------------|
| | 501-D13 (Rc = 9.5:1) | Advanced Turboprop (Rc = 25:1) | 501-D13 | Advanced Turboprop |
| 1 | 33 | 38 | 102 | 60 |
| 2 | 33 | 40 | 89 | 84 |
| 3 | 37 | 54 | 77 | 88 |
| 4 | 39 | 74 | 65 | 72 |
| 5 | 41 | 84 | - | 64 |
| 6 | 89 | 86 | | |
| 7 | 91 | 88 | | |
| 8 | 91 | 90 | | |
| 9 | 95 | 94 | | |
| 10 | 95 | 96 | | |
| 11 | 95 | 98 | | |
| 12 | 95 | 100 | | |
| 13 | 95 | - | | |
| 14 | 91 | - | | |
| <hr/> | | | | |
| Totals | 1020. | 942. | 333. | 368. |

A "Functional" section could be added to the propulsion system parts list, which would group standard parts into functional categories such as bolts, nuts, washers, etc. This listing could then be analyzed by a Value Engineering group to reduce the number of parts to a practical minimum. This approach is even more appropriate when a systems approach such as the one described herein is used, where more than one manufacturer is involved. The different standards of the companies involved would tend to proliferate the number of standard parts in use.

4.3.4.1 Compressor

The power section of the propulsion system is shown in cross-section on Figure 4.3.1-2. It consists of a twelve-stage compressor with variable geometry in the inlet guide vanes and the first five stages, to produce an overall compression ratio of 25:1, or an average stage loading of 1.308 per stage. The compressor rotor is supported on two bearings; a front roller bearing mounted in the forward frame assembly, and a rear ball bearing mounted in the inner diffuser housing to react thrust loads. These loads are carried to the outer casing through a series of integral struts in the diffuser aft of the compressor exit, which do not appear in the figure. The rotor drum is a one-piece welded construction between stages two to nine, with the remaining stages and end shaft attached by conventional pilots and bolts. All blade rows except the first are attached by circumferential dovetails; the first is an axial dovetail. This combination is the result of a study that was made to minimize total rotor weights.

4.3.4.2 Diffuser and Combustor

Air leaving the compressor passes through a tri-axial diffuser which splits it into three separate flows; the primary center flow, the outer combustor flow and the inner combustor flow. The center flow of air passes through air-blast swirlers in the fuel nozzles, and through the forward wall of an annular combustion liner into the primary combustion zone. The inner and outer airflows enter the combustion liner through both primary and secondary orifices, as well as through cooling slots in the combustion liner wall. Cooling of these walls could be accomplished through transpiration cooling, using DDA Lamilloy material, if temperature and life requirements so dictate.

4.3.4.3 Turbines

The high pressure turbine which drives the compressor consists of two stages each with aircooled blades and vanes, separated

by a spacer/interstage seal. This turbine is cantilevered from the center ball bearing, which is also the rear compressor thrust bearing.

The low pressure power turbine is a three-stage free turbine assembly supported by two bearings; a roller bearing in the rear support and a thrust reacting front ball bearing which is co-axial with, and supported by, the HP rotor thrust bearings. This unique arrangement causes opposing thrust loads in each rotor to cancel out, resulting in a very moderate unbalanced thrust load to be transmitted through the static support structure. The front stub shaft of the LP turbine assembly is splined to an extension shaft which transmits torque to a coupling at the front of the power section forward support. The static structures shown are typical for this type of engine, and are based upon the existing DDA XT701 turboshaft engines.

4.3.4.4 Engine Accessory Drive

The accessory gearbox, which is mounted on the bottom of the forward support, is also similar to the gearbox on the XT701 engine, although the accessories being driven are somewhat different. The fuel control, for example, is considerably different from the hydro-mechanical unit on the XT701 engine, since the primary fuel control on this engine is a full authority digital electronic control (FADEC).

4.3.4.5 Background

Although the power section depicted in Figure 4.3.1-2 represents a correctly sized aerodynamic flowpath with the correct number of stages and general arrangement, it is not a completed engine design in that only preliminary stress analyses of new hardware have been completed. It should be noted that the compressor is based upon the existing DDA Model GMA-100 compressor, with a "zero" stage and an "nth" stage added to boost the flow and pressure ratio to the required levels. Furthermore, the technology required to design and produce the new hardware items, such as the turbine airfoils, is well in hand and has been successfully demonstrated in other DDA engines. For example, the DDA Model GMA-200 engine has demonstrated turbine blade cooling techniques for burner outlet temperature levels far beyond those contemplated for this type of engine, using advanced transpiration cooling techniques. Other DDA engines have successfully demonstrated impingement and film cooled airfoils and endwalls. These techniques, coupled with advanced technology materials currently in use, ensure that the design of an advanced turboprop power section such as the one shown is possible within the reliability and life goals.

The detailed design process which would be followed to evolve a completely designed power section to meet the specified life requirements would start with the definition of a specific set of design criteria. These criteria would not only include all of the guidelines outlined in Appendix A of this report, but would specifically define detail requirements for the individual elements of the engine. These specific details would be based upon the life and duty cycle requirements of the application and would also include the results of the reliability apportionment analysis. This analysis would define the number of standard deviations on material property values to be used based upon the degree of risk to be tolerated for the specific element being designed. For rotating elements, a further refinement would be added, which would include a reduction in material strength values, based upon an empirically derived relationship of design, maximum allowable, and burst speeds of the rotating elements. For those rotating elements subject to stress rupture analysis, such as turbine blades, an additional degree of conservatism is introduced by adding factors to the standard Larson-Miller stress rupture relationship. These include an empirically-derived allowance of 35° which is added to the calculated metal temperature to allow for turbine temperature overshoot during accelerations; a long life divider factor which takes into account the form of the element, as related to standard bar data material properties; and a degradation factor which takes into account the effect of creep relation due to thermal gradients within the element. These examples are presented to illustrate the degree of conservatism which is built into the engine by virtue of the Design Criteria document, to ensure that the final design is capable of meeting or exceeding the design objectives.

Other factors, built into the power section design as standard procedures, which have been evolved as the result of many years of engine development and testing, also improve the probability of meeting the design objectives. Compared to the 501-D13, these would include such things as improved modular construction, better condition monitoring instrumentation, better borescope inspection access, etc. Current designs include dual labyrinth seals, supplied with pressurized air, to preclude leakage and minimize oil loss at all sumps. Improved materials in the seal stators also increase the life of the seals. Since seal wear may cause performance degradation, long life seals will help prevent premature removals for low performance. Advanced materials are also in common usage on current engines, including titanium alloys in the compressor rotor, and advanced nickel alloys coupled with directional solidification in the turbine section.

The main bearings used in engines being designed today have been vastly improved by comparison with those in the 501-D13 engine. For example, the previously-used criteria of a "B10" bearing life (10% failure rate) has been replaced with an "L1" criteria (1% failure rate). This improvement has been made possible by better quality materials and processing, including such things as grain flow control and elimination of foreign material inclusions. Design improvements such as through-bearing oiling, coupled with a much broader test basis for life-vs-load predictions have contributed materially to this progress. Although some of these improvements have increased the original cost of the bearing, the overall cost-of-ownership has been reduced considerably by virtue of the increase in operational life of the bearing.

Improvements in compressor design are evidenced by the variable geometry present on the advanced power section, which results in a significant improvement in off-design performance. The fewer number of stages is also indicative of the increase in stage loading of the newer compressor, achieved with no decrease in overall efficiency. This results in fewer blades and vanes subject to FOD and replacement. In the event FOD does occur, the circumferential dovetails permit the replacement of moment-weighted pairs of blades by simply removing half of the compressor casing. This design also permits the use of a welded rotor drum which is inherently much stiffer than individually stacked stages. This increased stiffness results in better blade tip clearance control and less seal wear. The welded construction also reduces fabrication costs and, consequently, overhaul costs.

Improvements in the combustor include better methods of cooling the liner walls, to eliminate hot spots, buckling, etc., and consequently increase the life expectancy of the liner. The basic conversion from the can-type combustors in the 501-D13 engine to the annular combustor in the advanced turboprop power section has resulted in a significant improvement in the BOT circumferential pattern factor, which in turn minimizes the thermal gradients in the turbine vane and blade rows. The net result is an improvement in the life expectancy of the entire hot section of the engine. The annular combustor is also equipped with air-blast fuel injection nozzles, which improve primary zone mixing and combustor efficiency and reduce the level of emissions from the power section.

The turbine section of the advanced turboprop power section has considerably improved airfoils compared to the 501-D13 engine. This is the result of not only improved aerodynamic design techniques, but much more sophisticated computerized programs which extend the capacity of the aerodynamic designs to explore minute

variations in design parameters, and to optimize airfoil designs over a much broader range of criteria. The net result is a significant improvement in the work extracted per stage, and a reduction in the number of stages. For example, the 501-D13 engine extracts approximately 5,000 HP in four total stages, while the advanced turboprop extracts approximately 13,000 HP in a total of five stages. This results in a lower first cost, as well as overall cost-of-ownership. Furthermore, the life expectancy of the advanced turboprop turbine airfoils is higher than those of the 501-D13 engine by virtue of improvements in cooling techniques, which minimize temperature levels and thermal gradients in the airfoils. Also, improvements in analysis techniques, such as a cumulative damage Larson-Miller stress rupture program currently in use, have improved the ability of the design engineer to more accurately predict actual life expectancy.

In general, it can be said that advancements in the state-of-the-art in numerous areas have vastly improved the capability of the advanced turboprop power section to meet the targeted design goals, as compared to the 501-D13 engine, which originated some 25 years ago.

4.3.5 Control and Fuel System

4.3.5.1 Approach

The design approach of the integrated propulsion control system provides for high reliability to require less maintenance than prior systems consistent with the requirements of lower cost of ownership and high dispatch reliability. The design approach will incorporate a high level of redundancy in required critical functions to achieve the necessary system integrity. The design approach shall include the following features:

- Integration of control functions of power section and advanced propeller to minimize number of system components.
- Utilization of a full authority digital electronic controller incorporating low power, large scale integration solid state components for high reliability for control of both the power section and the advanced propeller.
- Self check capability to detect and provide indication of the occurrence of a malfunction of any of the separate control system components.
- Optimum location and mounting of the control system components for easy access for routine maintenance and replacement. The electronic controller shall be located in a suitable thermal and vibration environment for long life.
- Provisions for remotely actuated devices for all adjustments which may be required in service.
- Provisions for automatic thrust management incorporating ability to select and maintain a selected number of power control modes for maximum efficiency (takeoff, maximum climb, maximum cruise as a minimum).
- Provision for interface, through digital data link, with the air-frame Flight Control Systems.

The capabilities of the digital controller to perform control system self checking, and malfunction detection, and isolation of faults to component level will greatly improve maintenance effectiveness. Maintainability studies on the 501-D13 control system (Reference 3) indicates that a primary problem existed in proper diagnosis of malfunctions resulting in "shot-gun" type maintenance. The ability to accurately isolate faults will provide a significant improvement in maintenance.

The electronic control employs various techniques for detecting faults in the separate control modules, correcting for them wherever possible, and protecting the engine from damage. A very simple fault indication is provided for the flight engineer with more specific information for maintenance purposes such as flag indicators to isolate defective modules. The maintainability goals set for the control units are:

- Simple fault identification and isolation
- Easy access and removal from engine
- Repairability
- Minimum field service requirements with minimum setup adjustments. Modular replacement independent of other modules and sensors; that is, any module (electronic unit, hydromechanical unit) can be removed and replaced without requiring any calibration or setup.

The electronic control shall provide, through a suitable data link, parameters which are available in the engine control program for a condition monitoring system. These output signals may be used in the airframe for engine condition monitoring and are also available for bench test of the control components.

4.3.5.2 Control Features

All control functions for the engine and advanced propeller for optimum thrust management throughout all the required operational conditions would be provided by the control and fuel system. The system would perform the following functions:

- Automatic built in control/advanced propeller system self test for pre-start and operation monitoring.
- Automatic start sequencing
- Power turbine inlet gas stream temperature limiting during all operation, including start, for turbine protection
- H.P. turbine blade temperature limiting for extended turbine life.
- Control acceleration and deceleration fuel flow, bleed and compressor geometry for smooth and rapid operation without surge or flame out.

- Control gas generator speed as a function of power lever input position to provide modulation of engine power from max rating to idle to max reverse.
- Control advanced propeller/power turbine speed over the required operational range.
- Limit maximum power turbine overspeed by an independent back up control function.
- System for autofeather operating thru advanced propeller hydraulic system.
- Provisions for torque limiting for gear box protection.
- Provisions for automatic mode selections for optimum thrust control (takeoff, maximum climb, maximum cruise as a minimum).
- Provisions for digital link interfacing with flight control system for automatic propulsion control throughout all regimes of engine operation.
- Propeller synchrophasing

The conceptual design of the integrated advanced turboprop propulsion system control to accomplish these requirements is shown in block diagram form in Figure 4.3.5.2-1. This control system will utilize an advanced technology, high reliability, digital electronic controller. The electronic control will provide all control computations., scheduling, logic, interlocking and sequencing of all engine and advanced propeller functions. In addition, the unit provides built-in test capabilities to continuously monitor the various elements of the control system for malfunctions, and provides indications of failures. The electronic control also incorporates interface communication of the propulsion system with aircraft control computers. The control system is thus fully compatible with a "fly-by-wire" aircraft system.

An integrated fuel handling system will include the functions of fuel pumping, fuel metering, fuel cut-off and working fluid for compressor geometry actuation.

The fuel flow module will incorporate suitable electrical interfaces for operation with the electronic control for fuel metering and compressor geometry actuation control. This electrical/mechanical device requires close design attention to achieve the required integrity to provide for reliability in this critical interface mechanism. Means of achieving redundancy in this critical area should be a subject for further development.

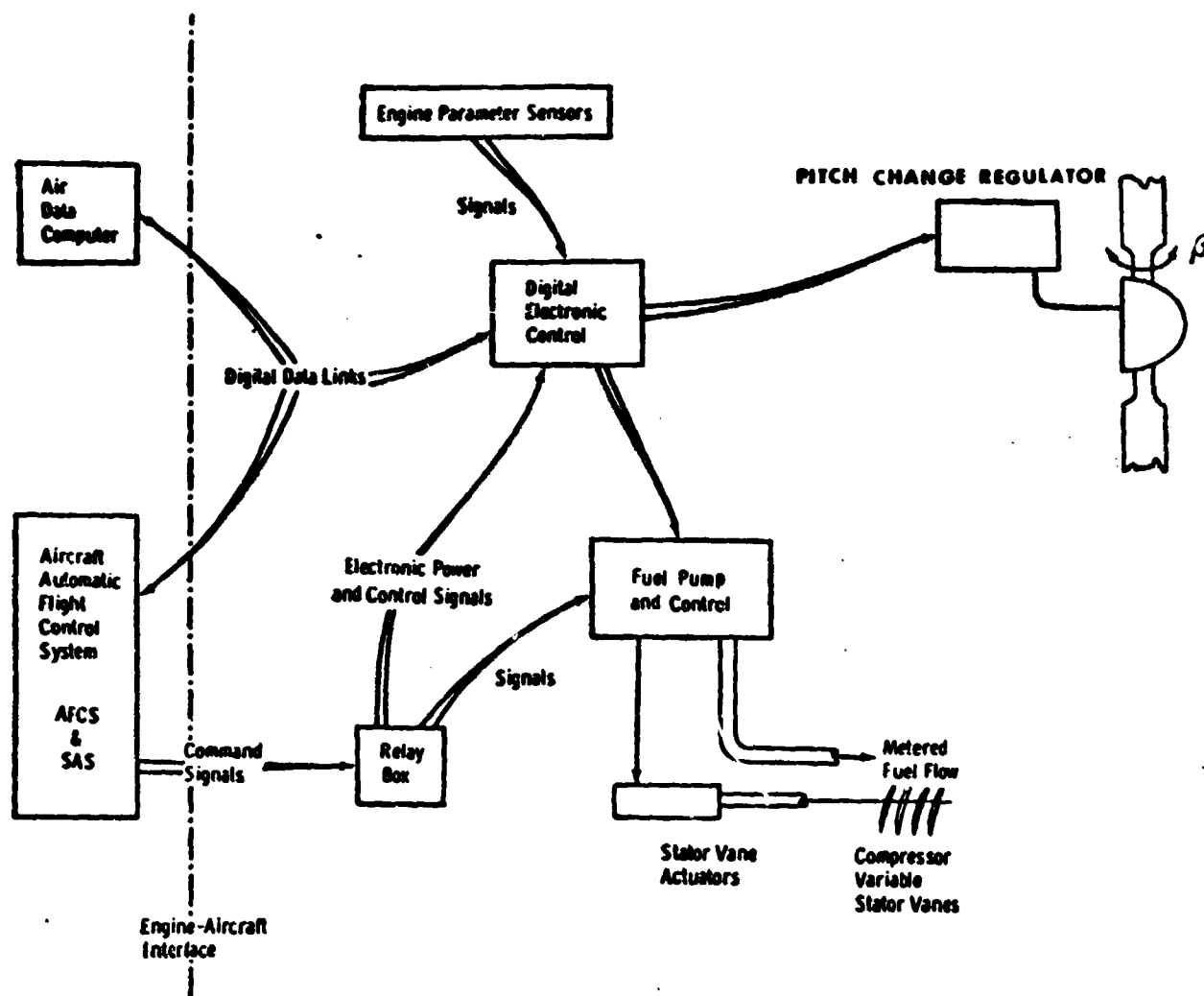


Figure 4.3.5.2-1. Advanced turboprop propulsion system control block diagram.

The fuel flow module will also incorporate features to implement detection of malfunctions in the pumping system, fuel metering system, or the compressor actuation control. These malfunction detection features will be designed to interface with the digital controller as a portion of the overall malfunction detection system.

Advanced propeller blade pitch control will be handled by the digital controller, utilizing electronic speed sensing and operating through an electrohydraulic servovalve to control the separate pitch actuation mechanism. Means of achieving redundancy in this servovalve interface should also be the subject for further development to assure the required reliability in the critical area. The pitch control system shall also incorporate features for implementing detection of a malfunction as an integral part of the digital control system.

4.3.5.3 Control System Operation

A two-lever system is envisioned for control of the propulsion system. The power lever will control thrust from maximum through idle and into reverse operation; the condition lever, by discrete positions, will select "run", shutdown and advanced propeller feather.

This control system will minimize the pilot work load by incorporating many of the limiting and optimizing functions which normally require pilot effort. Because of the computational and logic capabilities of this approach, many advanced control features can be incorporated. For example, the coordination between the advanced propeller pitch control and the gas generator can be tailored to provide optimum overall propulsive efficiency at any long duration flight condition, and can also be optimized to provide fast thrust response and minimum noise levels for takeoff and landing conditions. Dynamic compensation will be included which is a function of the operating conditions to optimize system stability and response characteristics throughout the envelope. Synchrophasing will be included in the normal control logic. The control will incorporate self-checking features and will be programmed to employ alternate control modes in the event of loss of individual sensors or control functions. Diagnostic routines can also be included which can be displayed to minimize troubleshooting time in the event of a system malfunction.

Initial studies indicate that the power setting functions will be established by controlling gas generator speed in a manner similar to present-day turboprops or turbofan engines. The power setting schedule will be a function of compressor inlet temperature (and Mach No. or ambient pressure if required) and incorporate the desired turbine temperature, turbine blade temperature, maximum speed, torque and thrust setting limits. The gas generator control will include the schedules for modulating compressor variable stator vane geometry, probably as a function of compressor speed and inlet temperature. Acceleration and deceleration limits will be incorporated to avoid compressor surge during power changes. These limits

will probably continue to use fuel flow divided by compressor discharge pressure as a function of gas generator speed and inlet temperature.

Figure 4.3.5.3-1 shows a block diagram of the typical control functions which would be used in the basic control mode. Detail performance and dynamic studies are required to define the schedules and optimize the system steady-state and dynamic performance characteristics and the safety and diagnostic routines. However, the use of an integrated digital electronic system to coordinate the advanced propeller and power section control functions provides a great deal of flexibility to incorporate those features which are required to provide a truly optimum and safe control system.

4.3.5.4 Hydromechanical Components

The fuel handling components of the system shall be conservatively designed for high reliability and ease of maintenance. A single integrated hydromechanical assembly will include the functions of fuel pumping, metering, shut-off and fluid supply for compressor geometry actuation. Suitable filtration will be provided upstream of the pump to minimize the effects of contaminants on all the hydromechanical components. The system shall be capable of operation under specified conditions of vapor/liquid at the fuel inlet. The pump shall utilize proven technologies for long life, highly reliable operation on commercial fuels, including JP4, JP5, jet kerosene (ASTM 1655-65T), hydrafine processed fuel, and higher thermal stability limit fuels.

The unit shall include a suitable, highly reliable electrical interface with the electronic controller for metering valve actuation. Provisions shall be made for suitable means of detecting malfunctions of the interface device and of the system pressure compatible with the system check by the electronic controller. The system shall incorporate adequate redundancy features to provide back-up operation of the fuel metering and compressor geometry functions in the event of failure of the primary electronic control. Reversion to back up operation shall be pilot initiated. In the back up mode the system shall provide for modulation of thrust over the range of idle +5% to 90% maximum.

4.3.5.5 Digital Electronic Controller

An advanced technology digital electronic controller shall provide all control computations, scheduling, logic, interlocking and sequencing of all engine and advanced propeller functions. The controller shall utilize low power, large scale integration, solid state components for high reliability. The controller assembly shall have the following features:

- Suitable signal conditioning and A/D conversion for all control parameters from the power section sensors and position feedbacks. Provisions for redundant sensors shall be made where required for acceptable operational integrity.
- Proportional power signals for the control system effectors to the fuel metering valve, compressor geometry actuator and advanced propeller pitch control.
- Necessary control discretes.
- Built in test capabilities to continuously monitor the controller and software functioning as well as monitoring the various elements of the control system for malfunction. Suitable means of indication of the malfunctions shall be provided to accurately isolate control system assembly problems for maintenance action.
- Provisions shall be made for suitable digital data links for communication with aircraft flight control system, air data computer, condition monitoring equipment and other ground support equipment.
- The controller shall be designed for the specified environmental conditions using conservative design approaches for minimum temperature gradients in the circuit assemblies with a maximum allowable temperature at any point in the assembly of 200°F.
- The controller and total control system shall be designed in accordance with electro-magnetic compatibility requirements of MIL-STD-461.
- Maintainability - The electronic controller shall be designed with the following maintainability adjectives.
 - "On condition" maintenance
 - Minimal test support equipment
 - Modular construction
 - Simple high reliability connections
 - Interchangeability of sub-assemblies
 - No special tools required

- Electrical connectors - A minimum number of electrical connectors shall be used and shall conform to MIL-C-83723, Series 3, Threaded, Class H or R.

Figure 4.3.5.5-1 illustrates a control system interface diagram of a full authority digital controller for the advanced turboprop propulsion system.

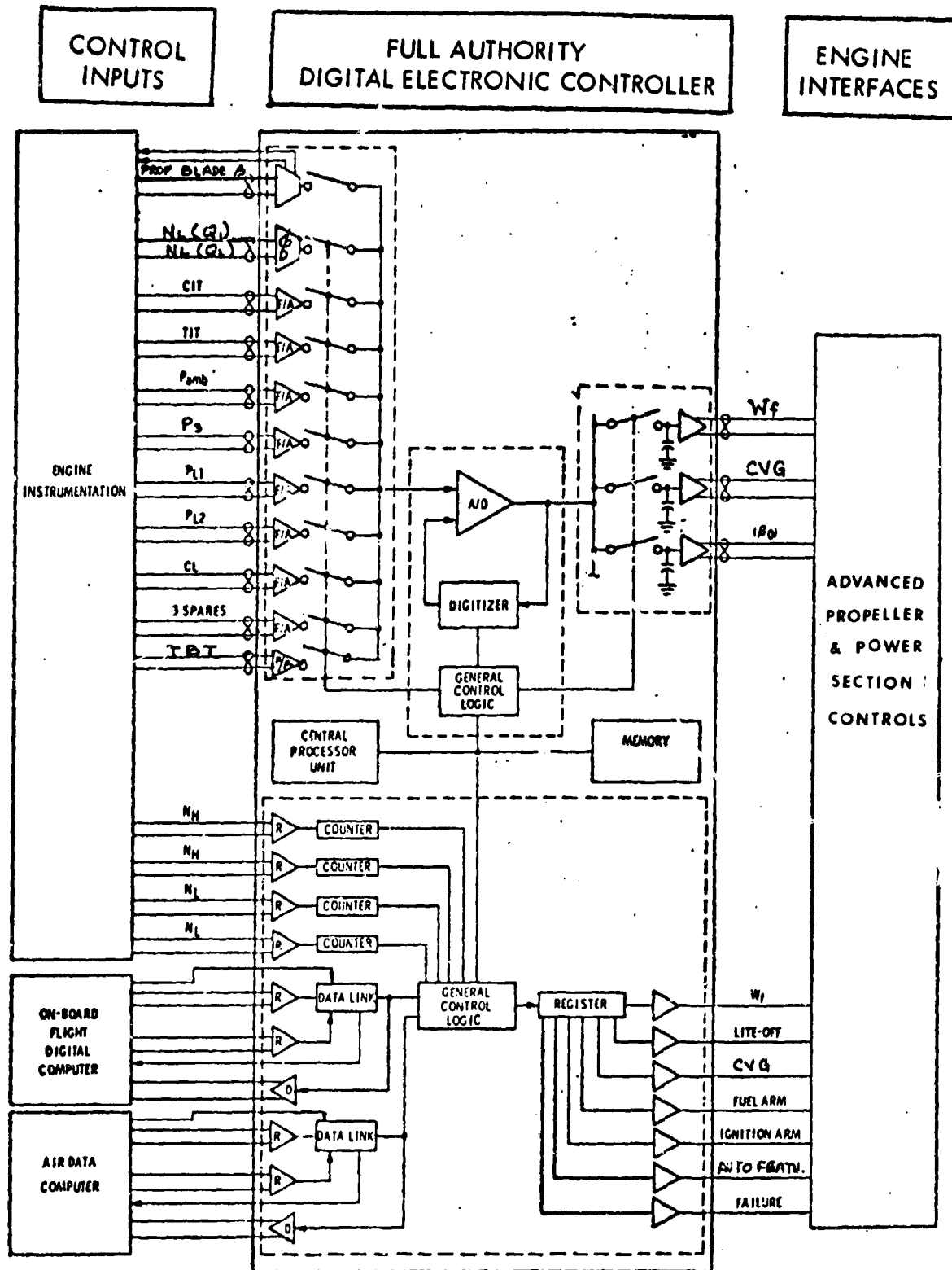


Figure 4.3.5.5-1. Advanced turboprop propulsion system control interface diagram.

4.3.6 Lubrication System

The advanced turboprop lubrication system will be similar to the 501-D13 engine but will include an integral oil tank and oil cooler as in the XT701 engine. Another improvement will be the integration of the advanced propeller, power section and reduction gear systems, eliminating pumps usually buried within the propeller. Engine condition monitoring components will be added and conventional lube system parts will be updated and upgraded to improve reliability and maintainability.

The turboprop requires much greater heat exchanger capacity than the turbofan due to the gear and bearing friction losses in the reduction gearbox. An air-cooled heat exchanger is needed rather than the fuel-cooled type presently utilized by most turbofans. A nacelle duct and duct door with anti-icing provisions are usually required with air-cooled heat exchangers.

Engine condition monitoring systems generally include oil quality measurement devices that detect in an early stage many types of part failure such as wear and contact surface fatigue spalling of gears and bearings. With the advanced propulsion system separable into modules, and since a common oil system will be used, it is very desirable to be able to identify the module that is failing and to isolate failure debris to that module. A selective or multiple oil condition monitoring unit/units must therefore be incorporated into the lubrication system. Isolation of debris must be accomplished nearly as efficiently as is current pressure system filtration. Magnetic or high capacity filters will thus be necessary in the scavenge system after the chip detectors and screens. Successful failed module identification and debris isolation, together with the greater modularization, will minimize replacement and repair in event of failure with resultant decreased repair cost, decreased module inventory investment, and improved equipment availability.

The DDA XT701 accessory drive assembly design greatly simplified the required plumbing by integration of many small oil system components (valves, switches, transducers, etc.) into or onto the accessory drive housing. Interconnecting lines were cored into the housing. Oil lines were reduced from 23 to 10 resulting in decreased connection points and improved maintainability as well as less weight and cost. The same design philosophy will be followed for the advanced turboprop propulsion system.

The use of an LP driven pump on the reduction gearbox introduces some question concerning its integration into the lubrication

system. Currently it is envisioned that in event of an HP rotor system failure, the LP driven pump will perform like an emergency system to supply low pressure minimum oil flow to LP drive system bearings only. Since gearbox power train loads will be low as will the LP rotor thrust bearing, gear and bearing cooling needs will be low. Detail design studies will be required to determine if scavenging from the power section may be possible; if not, unlimited operating time may not be available. Complete details of such a system can best be developed in context with a final engine design.

4.3.7 Power Section Accessory Drive Assembly

The advanced power section accessory drive assembly is mounted on the bottom of the power section air inlet housing. It is driven by the HP rotor through a bevel set in the air inlet housing hub, a radial drive shaft and a second bevel gear set in the accessory drive assembly. Accessory drives are provided for a starter, fuel pump/fuel control, oil pump, magneto power supply, centrifugal air/oil separator and an electrical indication of the HP rotor speed. This unit is essentially the same arrangement as that on the DDA XT701 engine. It will be designed to the following requirements which reflect the increased reliability, and maintainability features typical of current design practices.

- Positive oil lubrication will be provided for the drive splines of the starter, fuel pump, and oil pump.
- Accessory shaft seals will be externally removable and capable of withstanding a 5 inch Hg. pressure drop.
- Bevel gearing will not have maximum continuous operating stresses in excess of 30,000 psi in bending and 250,000 psi in crushing using Gleason formulae. The bending and crushing stresses for the starter proof load will not exceed 60,000 psi and 400,000 psi respectively.
- Spur gears will not have maximum continuous operating bending stresses in excess of 30,000 psi and crushing stresses in excess of 140,000 psi. The bending and crushing stresses for the starter proof load will not exceed 60,000 psi and 270,000 psi respectively.
- Accessory gear bearings will employ flanged outer races. Inner races will be clamped. The inner races will be sep-

arable from the shafts. Bearing life will be 35,000 hours with normal operating loads and at a level to meet the reliability requirements established for them.

- means of rotating the gas generator rotor for borescope inspection will be incorporated in the gearbox.
- Handling pads to permit removal of the gearbox with all accessories in place will be provided.
- The fuel pump/fuel control will be driven directly by the level gears to improve system reliability.
- The fuel pump and starter will have provision for V-Band mounting to reduce replacement time.
- Accessories will be spaced to provide access for replacement without disturbing adjacent accessories.
- Capability to withstand crash loads of 20g fore and aft, 20g vertical and 10g side, with the accessories in place and intact will be provided.
- Gears shall be integral with supporting shaft wherever possible. Gears that must be splined onto a shaft must be supported on pilots on each side of the spline.

The total number of gears and bearings in the advanced accessory drive train are 9 and 13 respectively. These compare to 9 and 14 for the 501-D13 parts. While no significant reduction in part count has been made, life and reliability will be improved by bearing size selection for longer life and by the selection of roller rather than ball bearings at eight radial load locations. The roller bearings will have one-piece machined separators and the remaining ball bearings will have two-piece machined riveted separators. The two-piece stamped ribbon riveted separators currently used represent quality control problems and are prone to wear and loosening during long time operation. Additional reliability improvement over that indicated by fatigue life calculations should result. Calculated bearing set life improvement is expected to result in about ninety percent fewer failures than experienced by the 501-D13.

The starter required for the propulsion system should be very like that required to start a similar turbofan engine since only the HP rotor system is rotated. Use of a "standard" starter at about 7500 rpm drive pad speed is expected. In con-

trast, the 501-D13 engine uses a special starter mounted on a 14,239 rpm drive pad. The required starter should therefore be readily available, fully developed, more reliable, and less expensive than the 501-D13 starter.

4.3.8 Maintainability Features

Maintainability must be initiated as a major design discipline with the conceptual design studies to achieve the support cost goals for an advanced turboprop propulsion system. Maintainability features designed into the system will enhance the maintenance capabilities through modularization, reduced maintenance requirements and "on condition" maintenance concepts. The on-condition maintenance philosophy eliminates scheduled removals for overhaul or interim inspections. This is achieved in part through improved reliability and in part through related maintainability features.

The following maintainability features have been incorporated into a proposed design concept for an advanced turboprop propulsion system:

- Simplification of nacelle structure
- Modular main drive reduction gearbox
- Modular advanced propeller
- Modular power section
- Improved component accessibility
- System and component handling features
- Minimum interface connectors
- Maximum utilization of Quick Attach-Detach (QAD) system component mounting features
- Condition monitoring

4.3.8.1 System General Arrangement

The proposed general arrangement for the propulsion system (ref. Sect. 4.3.1) consists of:

- Advanced Propeller (Prop-Fan)
- Main Drive Reduction Gearbox
- Power Section
- Installation Parts

4.3.8.2 System Handling Features

- Nacelle
 - The nacelle provides for complete accessibility to perform routine servicing, inspection and maintenance.
- Prop-Fan
 - The Prop-Fan is removable as a module with the aid of support slings.
- Main Drive Reduction Gearbox
 - Reduction gearbox will be removable as a module utilizing separate handling points for attaching ground support equipment.
- Power Section
 - Power section accessory gearbox module support pad attach points for accessory gearbox removal with accessories attached.
 - LP turbine module with adequate mounting pads for power section aircraft mounting and separate pads/mounts for module replacement.
 - Engine handling attach points for total engine package replacement separate from aircraft mounts.
- Installation Parts
 - Will be conveniently removable or left in place dependent upon the module being replaced.

4.3.8.3 System Maintenance Features

The following maintenance features are included in the proposed advanced turboprop propulsion system:

4.3.8.3.1 Modular Concept - Prop-Fan

- Spinner
- Deicing Conduit Assembly
- Foreward Cover and Fairing
- Blades
- Pitch Change Actuator
- Disk and Fairing
- Transfer Tube Assembly
- Pitch Change Regulator
- Slip Ring Assembly

The Prop-Fan designed for this study incorporates numerous features to substantially improve maintainability over that achieved with current systems. Figure 4.3.2.1-1 presents the modular separation of the Prop-Fan

The proposed Prop-Fan has been designed to allow on-line module/component replacement or replacement of the Prop-Fan assembly, whichever is the expedient maintenance action. The usual action will be to replace only the failed module or component. However, there are some circumstances where removal of the Prop-Fan assembly would be appropriate, such as to replace a failed gearbox, or subsequent to severe accident damage to the Prop-Fan .

Due primarily to improvements in modularity, line remove/replace times for the Prop-Fan assembly or components have been significantly reduced when compared with current propellers. Table 4.3.8-I is a summary of Prop-Fan line remove/replace times compared with equivalent line remove/replace times for the HS 54H60 propeller. Note that in most cases the equivalent 54H60 line maintenance action is to remove/replace the entire 54H60 assembly. In some cases, it is possible to replace the 54H60 component which is equivalent to the Prop-Fan component, after removal of the 54H60 assembly from the aircraft, but additional shop time is required. For example, for blade replacement the Prop-Fan blade is compared with the 54H60 propeller assembly line maintenance action since the 54H60 blade cannot be replaced on the wing. If it is necessary to replace a 54H60 blade, the additional shop time required is 12 hours once the propeller assembly has been removed from the wing.

Prop-Fan shop maintenance times have also been reduced compared to equivalent 54H60 actions as a result of modularity and hardware simplification. Table 4.3.8-II is a summary of shop repair times for Prop-Fan component repairs compared with similar 54H60 component repair and overhaul times. The times listed are the average shop time for the respective component assuming that component alone has been returned to the shop; line remove/replace times or time to remove a component from the propeller assembly, if applicable, are not included. The Prop-Fan values have been estimated by the same HS overhaul and repair personnel who estimate charges for current propeller system repair orders. The 54H60 values are based on records of actual overhauls and repairs.

Table 4.3.8-I
Summary of Prop-Fan
vs
Comparable 54H60 Assembly and Component
Line Remove/Replace Times
(Minimum Aircraft Down Time)

| PROP-FAN | | 54H60 | |
|-----------------------|-----------------------------------|----------------|-----------------------------------|
| <u>Task</u> | <u>Elapsed Time (hrs)</u> | <u>Task</u> | <u>Elapsed Time (hrs)</u> |
| Prop-Fan Assembly | 2.0 | 54H60 Assembly | 4.0 |
| Spinner | .1 | Spinner | .3 |
| Regulator Assembly | 1.5 | Pump Housing | 4.5 |
| Pitch Change Actuator | 2.2 | 54H60 Assembly | 4.0 |
| Slip Ring Assembly | .2 | 54H60 Assembly | 4.0 |
| Blades, Pair | 1.2 | 54H60 Assembly | 4.0 |

TABLE 4.3.8-II

Summary of Prop-Fan
vs
Comparable 54H60
Assembly and Component Average Shop Repair Times

| PROP-FAN | | 54H60 | |
|----------------------------|-----------------|-----------------|-----------------|
| <u>Item</u> | <u>Manhours</u> | <u>Item</u> | <u>Manhours</u> |
| Spinner | 25.0 | Spinner - Front | 30.7 |
| Regulator Assembly | 48.9 | Pump Housing | |
| Variable Displacement Pump | 10.0 | Overhaul | 42.2 |
| Auxiliary Pump | 4.0 | Repair | 30.6 |
| | | Valve Housing | |
| | | Overhaul | 45.0 |
| | | Repair | 18.7 |
| Pitch Change Actuator | 22.4 | 54H60 Assembly | |
| Slip Ring Assembly | 10.0 | Overhaul | 205.5 |
| Blades (Individual) | 22.7 | Repair | 65.6 |

In reviewing the Prop-Fan repair times shown in Table 4.3.8-II it is important to realize they reflect the proposed "on-condition" maintenance philosophy. With this philosophy, detailed hardware analyses will be conducted during repairs to assure that refurbished units contain the latest configuration parts and that impending failures of still functional parts are identified and corrected prior to unit return to the field. With the maintenance concept of scheduled overhauls such as used with the 606 and 54H60 propeller systems, these detailed examinations occur only at overhaul, not during a typical repair. Thus the Prop-Fan repair times are representative of a maintenance action closer to a 54H60 overhaul rather than a 54H60 repair. Hardware simplification is evident in Table 4.3.8-II

by noting that Prop-Fan repair times are typically less than 54H60 overhaul times of comparable components.

4.3.8.3.2 Modular Concept - Power Section and Reduction Gearbox

- Reduction Gearbox
 - Prop Brake
 - Oil Pump
 - High Pressure Pump
- Power Section
 - Compressor/Diffuser
 - Combustor
 - HP Turbine
 - LP Turbine
 - Accessory Gearbox
 - Oil Filter
 - Lube Pump
 - Heat Exchanger
 - QAD (Fuel Pump & Fuel Control)

Figure 4.3.8-1 presents the modular separation of the power section.

Table 4.3.8-III presents a comparative summary of elapsed time (hrs) allocated for performance of selected maintenance tasks.

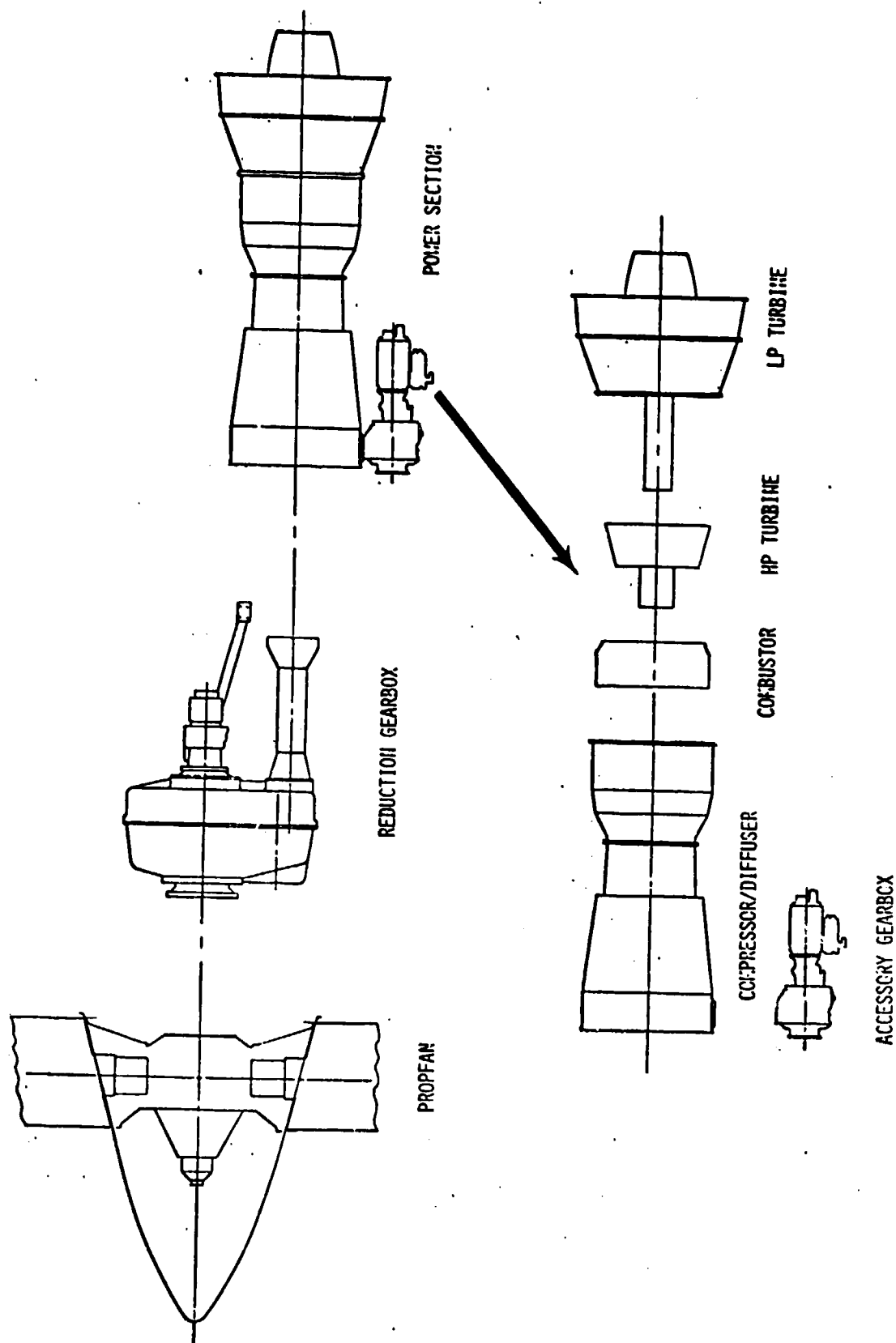


Figure 4.3.8-1. Advanced turboprop propulsion system modular assembly.

TABLE 4.3.8-III

Comparative Maintenance Tasks
On-Aircraft Remove/Replace Time (hrs)

| <u>Maintenance Task</u> | <u>Elapsed Time (hrs)</u> | |
|--|---------------------------|---|
| | <u>501-D13</u> | <u>Advanced Turboprop (Estimated)</u> |
| Power Section | 13.0 | 3.5 |
| Reduction Gearbox | 9.0 | 4.0 (1) |
| Power/LP Turbine | 3.0 (2) | 2.0 |
| HP Turbine | | 2.8 (3) |
| Combustor | (2) | 3.4 (4) |
| Fuel Control | 4.0 | 0.5 |
| Spark Igniter Assembly | 0.2 | 0.1 |
| Temperature Datum Control/ Electronic Control | 0.7 | 0.4 |
| Burner Drain Valve Assembly | 0.5 | 0.2 |
| Power Section Components (Average) | 0.9 | 0.3 |

(1) Includes 2 hr propeller replacement

(2) Single turbine and combustion chambers removed and installed as an assembly

(3) Includes power/LP turbine replacement

(4) Includes power/LP turbine and HP turbine replacement

The above values for the 501-D13 engine were obtained utilizing DDA field experience and the maintenance and overhaul manhour handbook prepared to establish warranty credit for work performed by the customer. For the advanced turboprop system the man-hours were predicted based upon actual and estimated task man-hours for the XT701-AD-700 engine which is similar to the study power section.

4.3.8.3.3 Inspection Capabilities

- Propulsion system accessibility
 - Nacelle clam shell sections
- System and component location
 - Major system and components located on bottom of engine
- Borescope inspection ports
 - Compressor inlet housing
 - Midstage compressor
 - Combustor (4)
 - HP-LP turbine
- Filter impending bypass indication (fuel and oil)
- Magnetic drain plugs
- All scheduled inspections can be performed with the propulsion system installed
- Design will permit radioisotope inspection
- A means to hand rotate the engine during borescope inspection

4.3.8.4 Comparative Propulsion System Maintainability Features

Table 4.3.8-IV presents a general comparative listing of maintainability features for the 501-D13 and the advanced turboprop propulsion system.

Table 4.3.8-IV

Comparative Maintainability Features

| <u>Maintainability Features</u> | <u>501-D13</u> | <u>Advanced Turboprop</u> |
|---------------------------------------|--------------------------------|---|
| Oil tank | Aircraft mounted | Integral with power section |
| Aircraft accessories | Reduction gearbox mounted | Remote A/C accessory gearbox mounted |
| Condition monitoring | None | System capability |
| Maintenance Requirements | Scheduled | On-Condition |
| Replaceable modules | Limited to large modules | Maximized for improved maintenance capabilities |
| Power section component accessibility | Limited by panel removal | Maximized by nacelle design |
| Compressor cleaning | Special ground support adapter | Built-in manifold |

Several other significant propeller maintainability features have been incorporated in the Prop-Fan design which are worthy of note:

- The only requirement for line rigging is to set the pitch change actuator to the pitch change regulator feedback LVDT.
- Requirements for line balancing after module replacement have been eliminated.
- The spinner anti-ice heater elements have been eliminated.
- A more durable sheet metal blade heater has been designed to replace the wire heater concept used on the 54H60 propeller (Reference Figure 4.3.2.1.1-2). This will reduce the number of blade heater failures and hence blade removals.

- Quick disconnect mounting provisions have been provided for both the pitch change regulator module and the slip ring assembly module to reduce line elapsed maintenance times. With current propeller systems, the propeller assembly must first be removed to remove the assemblies comparable to the pitch change regulator and slip ring.
- Blades can be individually replaced while the Prop-Fan remains installed on the aircraft. This is in contrast to the 54H60 whereby the propeller must be removed from the aircraft and the hub assembly split in the shop in order to replace a blade.
- Check valves are provided in the pitch change actuator to minimize oil spillage during actuator replacement.
- The Prop-Fan concept has more blades and a higher power loading (horsepower per disc area) than conventional propeller equipment such as the 606 and 54H60 propeller systems and hence will have a smaller diameter. A smaller diameter rotor located with greater blade tip to ground clearance should have significantly reduced frequencies of damage due to erosion, FOD, or accident.

4.3.8.5 Remote Mounted Aircraft Accessories

The advanced turboprop propulsion system aircraft accessory gearbox (Reference Figure 4.1.2-1) is remotely mounted. Accessories mounted on this reduction gearbox would include:

- Alternator
- Hydraulic pumps
- Aircraft system components

Although the aircraft accessory gearbox is not considered as part of the propulsion system, it is driven from the reduction gearbox and in addition provides for a maintainability modular feature. When replacement of the propulsion system is required, the remote gearbox eliminates the many disconnects for aircraft driven components formerly mounted on the main drive reduction gearbox.

4.3.8.6 Condition Monitoring

To implement the "on-condition" maintenance philosophy a condition monitoring system will be required. Advanced condition

monitoring techniques have been employed to assist in the detection and isolation of failures. This will result in reduced line maintenance requirements for troubleshooting and eliminate unjustified removals.

The following presents a condition monitoring system and a list of the suggested parameters.

Continuous monitoring of pertinent parameters is necessary to enable determination of basic propulsion system and/or propulsion system component condition. By considering these parameters early in the design phase, the sensors, pick-ups, transducers, wiring, etc. needed for measurement can be integrated into the basic propulsion system design. Built-in monitoring features include ease of installation, increased maintainability and improved reliability of design.

Selection of the pertinent parameters for monitoring is based on the following considerations:

- Parameters required for continuous cockpit display
- Parameters required for inflight safety determination
- Parameters required for ground maintenance indication on a per flight basis

Parameters satisfying the above criteria include:

- Continuous Display

- NP - Power Turbine Speed
- NG - Gas Generator Speed
- WF - Fuel Flow
- PTIT - Power Turbine Inlet Temperature
- POIL - Oil Pressure
- Q - Torque Signal

- Inflight Safety

- Continuous Display Parameters
- OIL - Oil Level (Full Oil, 1/2 Oil)
- TOIL - Oil Temperature
- CV - Compressor Vibration
- CBV - Center Bearing Vibration
- TV - Turbine Vibration
- RV - Reduction Gearbox and Propeller Vibration
- AV - Power Section Accessory Gearbox Vibration

- E/1 - Oil Quality and Flow (Prop-Fan and Engine)
- PFIL - Oil Filter Blockage Indicator
- ION - Ion Discharge Detector
- TBT - HP Turbine Blade Temperature

● Ground Maintenance Indication

- Continuous Display & Inflight Safety Parameters
- TT2 - Compressor Inlet Temperature
- PT2 - Compressor Inlet Pressure
- TT3 - Compressor Discharge Temperature
- PS3 - Compressor Discharge Pressure
- PT4.1 - Gas Generator Discharge Pressure
- CVG - Variable Geometry Position
- BVAL - Bleed Valve Position
- CBF - Customer Bleed Flow
- PL - Power Lever Position
- CL - Condition Lever Position
- SWX - Cockpit Switch Positions
- IGN - Ignition Voltages/Currents and Spark Rates
- CMV - Control Metering Valve
- BETA - Prop Pitch Input Signal
- ALT - Altitude
- MN - Mach Number
- Other considerations include:
 - A magnetic chip detector provided in the system to collect large metallic chips.
 - Prop-Fan regulator supply pressure and flow are monitored to assist in fault isolation.
 - Prop-Fan blade angle feedback from the LVDT will be monitored and compared with requested blade angle to check pitch change performance.

On board handling of the selected parameters will be the function of a specially designed computer whose tasks will include:

- Multiplexing incoming signals (multi-engine)
- Signal conditioning
- Analog to digital data conversion
- Fault tree processing (logic flow)
- Cockpit display interfacing (to cathode ray tube)
- Data recording (to external mass storage device)

System operation will consist of continuously monitoring the selected parameters via programmed logic flow while displaying required cockpit parameters on a CRT screen (bar form with limits and values imposed). If an inflight safety condition is detected by the logic, a warning will be flashed on the CRT with pertinent parametric values and limits and appropriate information as to emergency procedures required. If during the course of the flight a condition is detected which will require maintenance, diagnostic information will be displayed on the CRT at time of occurrence and redisplayed in summary after the aircraft has landed. External data recording onto a removable tape magazine unit will occur for each diagnostic encountered, by pilot command or during desired (programmed) events. Stored data will be used for history/trending studies at a designated central facility.

4.3.9 Reliability Assessment

A reliability assessment was made of the advanced turboprop propulsion system to provide the predicted improvements from the current system and to provide a basis for maintenance cost predictions. Assessment results were subdivided into several categories. The assessment results of turboprop functions were grouped separately from those of non-turboprop functions. Major module removals were identified separately from component and accessory removals.

4.3.9.1 Definitions

4.3.9.1.1 Major Module vs. Component/Accessory

The term "major module" was selected to represent those portions of the modularized propulsion system whose replacement times and complexity would be of the same approximate magnitude as for propeller removal and engine removal of current turboprop systems. Those items of the advanced modularized system which the study has indicated to be akin to current component and accessory changes have been included in the component and accessory category.

The success of the modular concept is illustrated by the effect on major module removal rates. For example, on current turboprop systems the replacement of either the 606 propeller regulator or the 54H60 pump housing required the removal and reinstallation of the entire propeller assembly -- a time consuming maintenance action of 4.5 hours. With the modular concepts embodied in the advanced turboprop system the comparable item can be replaced as a component in 1.5 hours. Therefore the replacement of similar items are not reflected in the major module removal rate projections but are added to the component/accessory removal rate estimates.

4.3.9.1.2 Inherent vs. Non-inherent Reliability

As defined in Section 3.5.2, inherent events are those caused primarily by propulsion system equipment failures. An assessment was made of the inherent reliability of the advanced turboprop system. The basis is discussed in section 4.3.9.3.

Non-inherent reliability is based on those events which are primarily not caused by propulsion system equipment. In order to make direct comparisons with airline rate and cost data which reflect total or "operational" removal rates and cost, an allowance had to be provided for non-inherent events. This allowance has the effect of increasing the removal rates beyond the inherent value or decreasing the MTBR

values below the inherent value. The non-inherent allowance provided for the effects of the following:

- Unsubstantiated/unnecessary removals
- Improper maintenance caused failures
- FOD
- Convenience to perform non-propulsion maintenance
- Accident damage

"Operational Reliability" is the term used to reflect the overall or total effect of combined inherent and non-inherent reliability.

4.3.9.2 Summary of Total Operational Reliability Assessment

The operational reliability assessment for the total advanced turboprop propulsion system is shown in Tables 4.3.9.2-I and -II. The values were used in the Maintenance Cost Model. Also shown are the values of the inherent and non-inherent rates used to arrive at the predicted operational rates. The inherent and non-inherent reliability assessments are discussed in the following paragraphs for these advanced turboprop propulsion system elements:

- Advanced propeller
- Advanced Main Drive Reduction Gearbox
- Core Engine and L.P. Turbine
- Power Section Accessory Gearbox, Components, and Accessories

These discussions of the reliability assessments are followed by a comparison of the projected advanced turboprop reliability with the current turboprop reliability.

4.3.9.3 Prop-Fan Reliability Assessment

4.3.9.3.1 Prop-Fan Inherent Reliability Assessment

The Prop-Fan design for this study offers advances in hardware configuration, complexity and modularity so different from current propellers that it was concluded the inherent reliability assessment must be made based on a piece part assessment of a preliminary Prop-Fan Parts list. This was done by using historical piece part failure rate data adjusted as required to reflect Prop-Fan operating conditions. The primary data sources were:

Table 4.3.9.2-I

Summary of Reliability Assessments of Advanced
Turboprop System Major Modules

| <u>Name of Major Module</u> | <u>Inherent Removal Rate/1000 hrs</u> | <u>Non-inherent Removal Rate/1000 hrs</u> | <u>Operational Removal Rate/1000 hrs</u> | <u>Operational MTBR, hrs</u> |
|------------------------------|---|---|--|----------------------------------|
| Propeller Disc | 0.0013 | 0.00156 | 0.00286 | 349,650 |
| Main Drive Reduction Gearbox | 0.030 | 0.010 | 0.040 | 25,000 |
| Core Engine | 0.160 | 0.040 | 0.200 | 5,000 |
| LP Turbine | 0.020 | - | 0.020 | 50,000 |
| Total for Major Modules | 0.2113 | 0.0516 | 0.2629 | 3,800 |

Table 4.3.9.2-II

Summary of Reliability Assessments of Advanced
Turboprop System Components and Accessories

| Name of Component or Accessory | Inherent Removal Rate/1000 hrs | Non-inherent Removal Rate/1000 hrs | Operational Removal Rate/1000 hrs | Operational MTBR, hrs |
|---------------------------------|--------------------------------------|--|---|--------------------------|
| Propeller: | | | | |
| Spinner | 0.0060 | 0.0026 | 0.0086 | 116,279 |
| Forward cover and fairing | 0.0038 | 0.0017 | 0.0055 | 181,818 |
| Deicing conduit assembly | 0.0008 | 0.0003 | 0.0011 | 909,090 |
| Pitch change actuator | 0.0232 | 0.0100 | 0.0332 | 30,120 |
| Blades (set of 8) | 0.0199 | 0.0260 | 0.0459 | 31,786 |
| Slip ring assembly | 0.0115 | 0.0049 | 0.0164 | 60,976 |
| Pitch change regulator | 0.0638 | 0.0274 | 0.0912 | 10,955 |
| De-ice timer (See Note) | (0.0191) | (0.0082) | (0.0273) | (36,630) |
| Pump, variable delivery | 0.1000 | 0.0430 | 0.1430 | 6,993 |
| Pump, auxiliary | 0.0030 | 0.0013 | 0.0043 | 232,558 |
| Transfer tube assembly | 0.0014 | 0.0006 | 0.0020 | 500,000 |
| Filter | 0.0013 | 0.0006 | 0.0019 | 526,316 |
| Sub-total for Propeller | 0.2347 | 0.1184 | 0.3531 | 2,832 |
| Engine: | | | | |
| Engine accessory gearbox | 0.0200 | 0.0050 | 0.0250 | 40,000 |
| Start system | 0.2000 | 0.1330 | 0.3330 | 3,000 |
| Electronic controls | 0.4000 | 0.1000 | 0.5000 | 2,000 |
| Fuel pump | 0.0150 | 0.0130 | 0.0280 | 35,714 |
| Oil pressure and scavenge pumps | 0.0032 | 0.0018 | 0.0050 | 200,000 |
| Ignition | 0.0018 | 0.0012 | 0.0030 | 333,333 |
| Minor accessories | 0.1500 | 0.0500 | 0.2000 | 5,000 |
| Sub-total for Engine | 0.7900 | 0.3040 | 1.0940 | 914 |
| Total for Accessories | 1.0247 | 0.4224 | 1.4471 | 691 |

NOTE: Values for De-icing timer are not included in totals since only one is required per aircraft

- Hamilton Standard experience with the 54H60 propeller operating on the P-3 aircraft. The data was accumulated by HS over the time period of CY 1965 through 1969. During this period 3,142,392 propeller hours were accumulated. The piece part data, the only HS propeller data of this detail which is available, was collected by HS service engineers who were stationed at the Navy operational and overhaul facilities.
- The Government-Industry Data Exchange Program (GIDEP), formerly the tri-service and NASA Failure Rate Data (FARADA) Program. Data from this source was used only when comparable HS piece part data was not available.
- Hamilton Standard experience with similar parts used in fuel controls and environmental control system products.
- Vendor data for like or similar parts.

Details of several specific piece part inherent reliability assessments based on historical field experience from the above data sources are presented below:

- Transfer Bearing. The fluid transfer bearing is used to transfer the pitch change actuator hydraulics from the stationary regulator to the rotating actuator. Failure is due to wear which results eventually in excessive leakage. Wear is a function of surface speed at the transfer bearing. A tabulation of the design parameters and the resultant Prop-Fan transfer bearing failure rate based on 54H60 propeller experience is presented in Table 4.3.9.3.1-I.

Table 4.3.9.3.1-I
Reliability Assessment of Fluid Transfer Bearing

| | <u>54H60</u> | <u>Prop-Fan</u> |
|--|--------------|-----------------|
| Diameter, inches | 6.5 | 3.5 in |
| RPM | 1020 | 1200 |
| Surface Speed, ft. per min | 1735 | 1100 |
| Failure Rate, Failures per thousand hours | .017277 | .010954 |

- Seals. Five different types of seals are used in the Prop-Fan design. Each seal was examined to correlate the Prop-Fan operating conditions affecting seal failure rate with the corresponding conditions of the seal application from which field service data and historical failure rates were derived. The results for each Prop-Fan seal type, expressed as a factor applied to the historical failure rate based on service experience are:

| <u>Seal Type</u> | <u>Primary Reliability Conditions</u> | <u>Failure Rate Factors</u> |
|------------------|---------------------------------------|-----------------------------|
| O-ring, Static | Temperature, Pressure | 1.00 |
| Lip Seal | Wear, seal surface speed | 0.42 |
| Blade Seal | Temperature, Wear | 1.00 |
| Translating Seal | Wear, Pressure Cycles | 1.00 |
| Actuator Seal | Wear, Pressure Level, Cycles | 0.50 |

- Primary Structural Items, Blades and Disc. These parts have of necessity always been designed for infinite life. There are numerous cases of specific 54H60 serial number blades and discs with accumulated operating time in excess of 35,000 hours (reference Section 3.3.2.2). Thus, with a design life of 35,000 hours the reliability of the Prop-Fan blades and disc is expected to be equivalent to current hardware. It should be emphasized that there have been no reported structural failures of 54H60 blades or discs.
- Blade Heaters. The proposed Prop-Fan blade heater has been designed to avoid many of the problems experienced with current 54H60 blade heaters (reference Sections 3.5.3.3 and 4.3.2.1.1 and Figure 4.3.2.1.1-2). Current blade heater failure histories were examined to determine which failures would be avoided with the new Prop-Fan design. The conclusion of this study was that the Prop-Fan blade heater failure rate would be reduced to 62% of that experienced for current 54H60 blade heaters.

- Variable Displacement Pump. Suppliers of variable displacement pumps were surveyed to determine current and projected (1985 - 1998 IOC) failure rates. The consensus of opinion was that an MTBF of 10,000 hours (0.100 removals per 1000 hours) will be achieved for pumps introduced in the 1985 - 1990 time period for applications like Prop-Fan. This represents a 25% to 50% improvement over current pumps operated in a commercial aircraft environment.

The above discussion of specific piece part reliability assessments highlights several areas where design improvements result in improved reliability. However, hardware simplification is the single most significant factor attributable to the substantial reliability improvement of the Prop-Fan when compared with current propellers. Based on total number of parts, current propellers are more than four (4) times the complexity of the Prop-Fan while the projected Prop-Fan reliability is nearly 2.25 times better than that of current propellers. Details of this comparison are provided in Section 4.3.9.3.3.

4.3.9.3.2 Prop-Fan Non-Inherent Reliability Assessments

In addition to inherent reliability, non-inherent reliability assessments were made for the following removal causes:

- Improper maintenance
- Unsubstantiated (no failure found)
- Foreign object damage
- Accident damage
- Convenience for other maintenance

Following is a discussion of the procedures used to estimate the non-inherent failure rates.

4.3.9.3.2.1 Improper Maintenance

Historical data was used to establish the failure rate associated with improper maintenance. Electra experience with the 606 propeller during CY 1965 and 1966 for Non-Unit Exchange Airlines was selected as the data base for the following reasons:

- This represented commercial propeller operation during a period of high utilization.

- Propeller removals reported during this period were categorized as to responsibility such that records of non-inherent causes of removal were available.

The propeller data was reviewed to establish the relationship between the number of cases of improper maintenance and the combined number of cases of inherent failures plus scheduled removals. The results indicated that the number of cases of improper maintenance was equivalent to 27 percent of the legitimate maintenance actions for the propeller. Since improper maintenance can only occur as a result of a maintenance action, it is assumed that the relationship of 27% should be applied to the inherent Prop-Fan failure rates to establish the failure rates for improper maintenance.

4.3.9.3.2.2 Unsubstantiated

Using the same propeller data source as above, the relationship between unsubstantiated and inherent failures was established as 32 percent for the propeller. Improved diagnostics, including fault isolation, as proposed for the Prop-Fan are assumed to reduce the previous level of unsubstantiated removals by a factor of two. Thus 16 percent of the inherent failure rate was established as the failure rate assessment for unsubstantiated removals.

4.3.9.3.2.3 Foreign Object Damage

The following analytical relationship has been established for purposes of predicting propeller FOD:

$$R = K \frac{DSF}{H}$$

where:

- R = Rate of Damage
- K = Constant of proportionality
- D = Sum of takeoff and landing roll distances
- S = Suction factor or disc loading
- F = Flight per 1000 hours
- H = Ground tip clearance

The relationship was developed by HS and has been confirmed by correlation against field experience.

Using the Prop-Fan design conditions including proposed aircraft mission and a representative FOD rate based on Electra Non-Unit Exchange Airlines data from 1965 and 1966, the Prop-Fan FOD rate was estimated to be 17.417 cases per million propeller hours, including bird strike damage.

4.3.9.3.2.4 Accident Damage

Based on information from the data base used in estimating improper maintenance and unsubstantiated failure rates, the Electra accident damage rate was found to be 3.991 events per million propeller/engine hours. The Electra blade tip to ground clearance is 15 inches versus 60 inches proposed for the Prop-Fan. The 60-inch blade tip to ground clearance is believed to be sufficient to clear plowed snow and most aircraft service vehicles such as baggage carts and refueling trucks as well as runway markers. Thus, the accident rate is expected to be reduced substantially. For this study, the rate was assumed to be 25 percent of the Electra rate or 0.998 events per million Prop-Fan hours.

4.3.9.3.2.5 Convenience

History indicates that convenience removals occur and are charged against the propeller (as well as the engine). Bookkeeping these removals against the propulsion system is considered improper and misleading in that they:

- Are not caused by the propulsion system
- Result in no needed maintenance correction nor shop cost to propulsion system component(s)

Therefore, no allowance was made in either Prop-Fan system removal rates nor maintenance costs.

4.3.9.3.3 Evaluation of Accuracy of Prop-Fan Reliability Assessment

Following is a summary of the Prop-Fan total reliability assessment, the actual unscheduled removal rate of the baseline current propeller system based on the HS 54H60/Saturn L-382 experience (reference Section 3.3.2.2 for the basis for selecting the L-382), and the baseline 54H60 data adjusted to reflect the Prop-Fan duty cycle of 1.25 hours per flight. All unscheduled removals have been used in this summary including component removals with the exception of the synchrophaser and deicing timer of which only one per aircraft is required.

| | <u>Failure Rate per 1000 Propeller Flight Hrs.</u> | <u>MTBF</u> |
|---------------------------------|--|-------------|
| Prop-Fan | 0.356 | 2,808 |
| 54H60/Saturn L-382 | 0.739 | 1,353 |
| 54H60 at Prop-Fan Duty Cycle | 0.800 | 1,250 |

The summary indicates a substantial improvement in propeller reliability (a factor nearly 2.25) has been achieved with the Prop-Fan concept. To correlate the Prop-Fan reliability assessment with the 54H60 experience two studies were conducted:

- A comparison on the basis of the number of parts
- An evaluation of the accuracy of prior assessments

The first study was a comparison of the 54H60 and Prop-Fan made on the basis of the number of different parts and the total number of parts. The results are summarized in Table 4.3.9.3.3-I. As indicated in the table, the Prop-Fan parts count, both on an assembly and component basis is substantially lower than for the 54H60. Based on total number of parts in the assembly and assuming that the mix of parts by reliability level were constant, a four to one (4.00 to 1.00) improvement could be expected in MTBF compared to the actual reliability improvement of 2.25 to 1.00. In conclusion, the ratio of parts count compared to the ratio of failure rates appears consistent with the mix of part type to be used in the projected Prop-Fan.

The second study was to evaluate the accuracy of the inherent reliability predictions by correlating them with actual field experience. The technique used to assess the inherent reliability of the Prop-Fan is the same as that previously used for predicting the inherent reliability of the 54460-1 propeller used on the E-2 and C-2 aircraft. The 54460-1 prediction was used for accuracy evaluation by comparing the propeller reliability assessment with actual field experience. The comparisons are summarized in Table 4.3.9.3.3-II and indicate that the actual overall reliability for the year 1976 was 134 percent of the predicted value. This substantiates the validity of the assessment technique for the following reasons:

Correlation of Advanced Propeller and 54H60 Reliability and Parts Count

*All failure rate values expressed as failures per 1000 hours.

- These results, based on experience during 1976, were achieved after only 26 months and 71,700 accumulative hours of propeller experience. The 54460-1 is a variation of the 54H60 propeller; it has the same pump and valve housing but the propeller assembly has a disc and blades of different design. As noted in Table 4.3.9.3.3-II, the actual failure rates were very close to the predicted rates for the pump and valve housing but significantly greater for the propeller assembly. This is consistent with experience based on DDA CV580 engine data in that it normally requires four years of operational experience for a variation of existing hardware to reach maturity. An examination of the propeller assembly failures indicates that over 75% were related to the hardware of new design. If the field data is adjusted accordingly, then the propeller assembly actual failure rate is very close to the predicted rate.
- Trend data indicates the failure rate is still declining as of the end of 1976. Reference Figure 4.3.9.3.3-1.

Table 4.3.9.3.3-II
Accuracy of Predicted Propeller Failure Rates
Compared to Field Results

| <u>54460-1 Component</u> | <u>Predicted Failure Rate</u> | <u>1976 Actual Failure Rate</u> | <u>Ratio Actual to Predicted Failure Rates</u> |
|--------------------------|---------------------------------------|---|--|
| Propeller Assembly | 139 | 337 | 2.42 |
| Pump Housing | 215 | 238 | 1.11 |
| Valve Housing | 148 | 99 | .67 |
| Total | 502 | 674 | 1.34 |

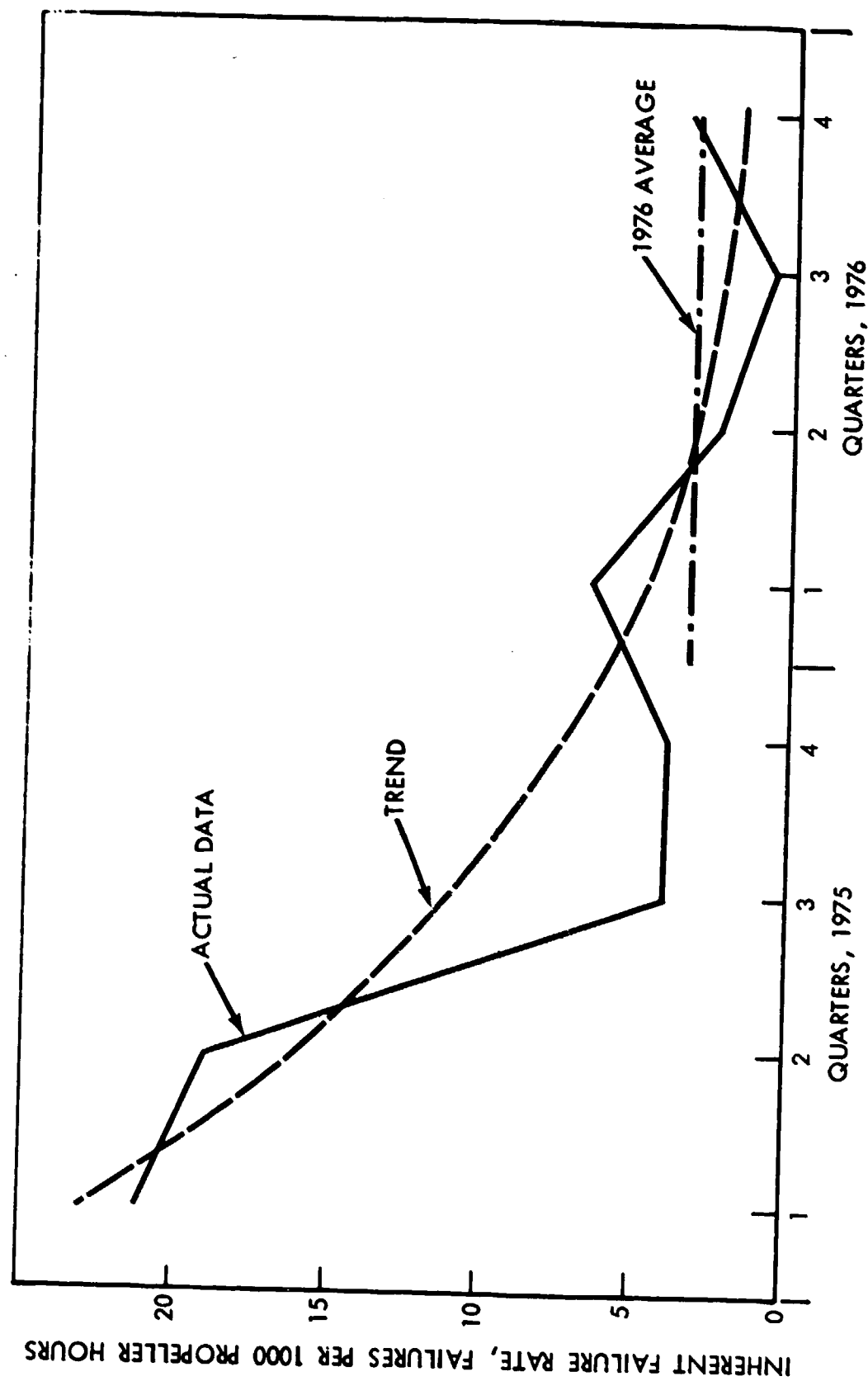


Figure 4.3.9.3 -1. 54H60-1 propeller assembly inherent failure rate

4.3.9.4 Advanced Main Drive Reduction Gearbox

4.3.9.4.1 Inherent Reliability Assessment for Gearbox

The assessment of the advanced main drive reduction gearbox, a major module, was based on 501-D13 experience. During the CY 1965-68 period there were 337 inherent 501-D13 reduction gearbox premature removals. These occurred with TBO's (maximum operation prior to overhaul) ranging from approximately 4000 hours to as high as 10,500 hours, with the weighted average approximately 7000 hours. Of these inherent removals:

- 37% were caused by failures in the accessory drives for aircraft accessories.
- 27% were caused by failures in the accessory drives for engine accessories.
- 36% were caused by failures in the main reduction gear drive system or in other characteristic turboprop functions such as propeller brake, safety coupling, and NTS.

The advanced main drive reduction gearbox contains those functions performed by the 36% represented above plus the limited accessory drive gears, bearings and associated hardware necessary to drive the lube pump, propeller high pressure pump and the power takeoff for the remote aircraft accessory gearbox. The advanced main drive reduction gear system can be compared directly with the corresponding portion of the 501-D13 gearbox.

During the CY 1965-68 period with the 7000 hr average TBO period, the 501 main drive reduction gear system accounted for:

- 120 inherent premature removals
- 32 non-inherent removals (based on symptoms and proportions)

These resulted in:

- An inherent premature removal rate of 0.048/1000 engine flight hrs (Equivalent MTBR = 20,770 hrs)
- A total, operational premature removal rate of 0.061/1000 engine flight hrs (Equivalent MTBR = 16,400 hrs)

The advanced main drive reduction gear system concept:

- (a) Contains less than half the number of power train bearings of the 501-D13
- (b) Contains proportionately fewer other hardware parts
- (c) Must be expected to operate for 35,000 hrs with no scheduled overhaul compared to every 7000 hrs average for the 501-D13 during the data base period.

Points (a) and (b) produce a favorable effect on reliability while point (c) tends to produce an unfavorable effect on reliability. To control and minimize this potential unfavorable effect, the advance design will incorporate bearing sizes selected for much longer life that will further increase reliability. Bearing set L10 design life characteristic for the advanced main drive reduction gear system is about 50,000 hrs under the higher horsepower operating conditions compared to the corresponding bearing set life for the 501-D13 main drive reduction gear system of 9700 hrs. Each of these were converted to an equivalent calculated failure percentage value at 7000 hrs, the average 501-D13 TBO period. The conversion was made using the Weibull distribution and a shape parameter, β , of 1.1. At the 7000 hr point, the advanced main drive reduction gear bearing set had corresponding failure percentage value of 1.02% and the 501-D13 power reduction bearing set had a percentage value of 6.8% as shown in Figure 4.3.9.4.1-1. Thus the advanced main drive reduction gear bearing set would be expected to have a 6.9:1 improvement over the 501-D13 set at 7000 hrs at the respective mean effective loads.

The demonstrated 501-D13 main drive reduction gear system inherent premature removal rate during CY 1965-68 was 0.0481 per 1000 engine flight hrs. This is equal to 0.337 per 7000 hrs (0.0481×7).

With the advanced main drive reduction gear system at 7000 hrs, the corresponding premature removal rate would be 0.049 ($0.337 \div 6.9$) per 7000 hrs (or an average of 0.007 per 1000 hrs during the 7000 hrs).

The predicted advanced main drive reduction gear system premature removal rate of 0.049 for 7000 hrs was extended to the planned advanced turboprop life of 35,000 by again using the Weibull distribution and $\beta = 1.1$ as shown in Figure 4.3.9.4.1-2. A rate of 0.049 at 7000 hrs extends to 0.29 at 35,000 hrs. This is equal to a premature removal rate of approximately 0.01 per 1000 hrs over the 35,000 hrs.

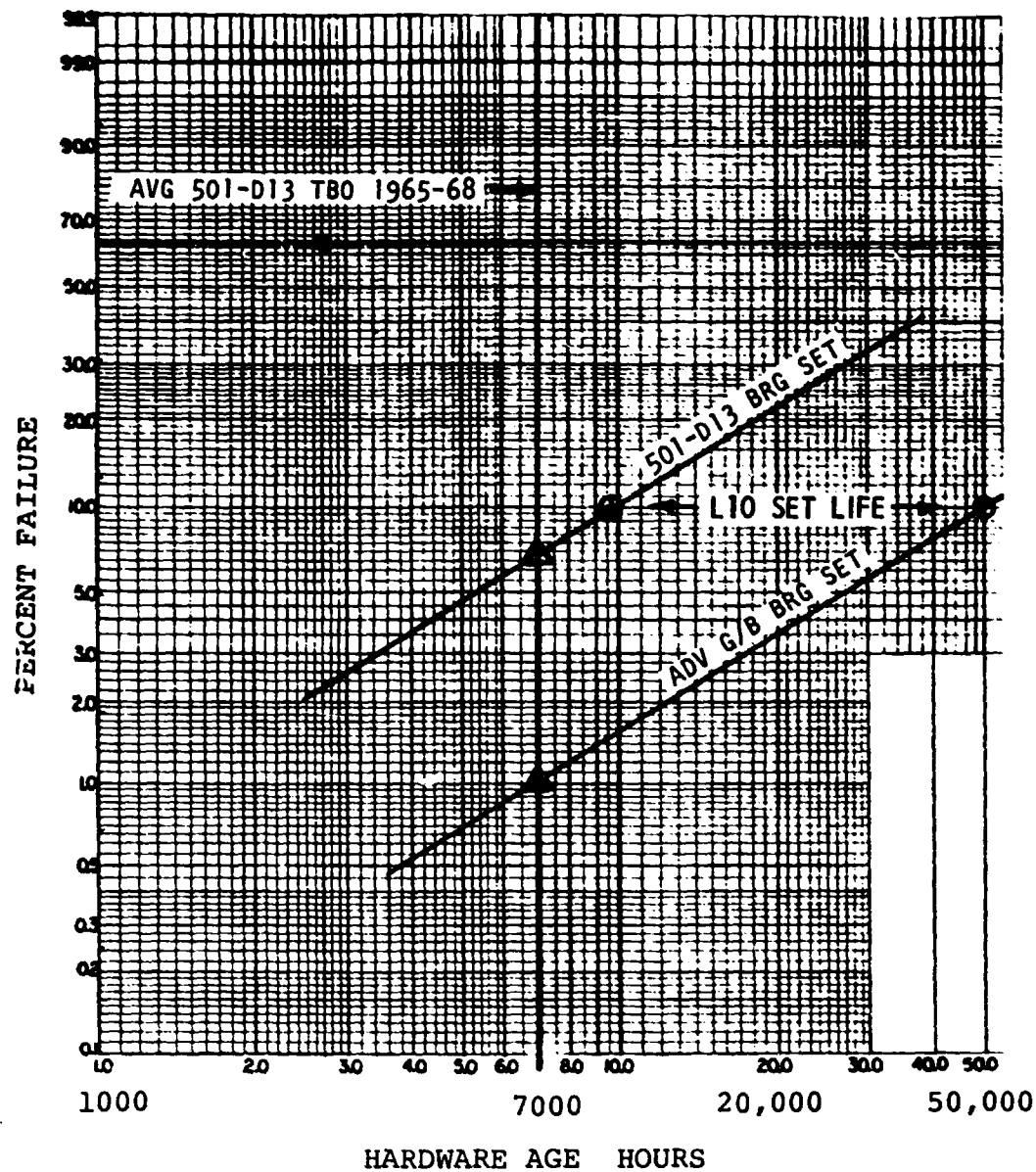


Figure 4.3.9.4.1-1. Determination of main drive reduction gear bearing set reliability at 7000 hr from average life points

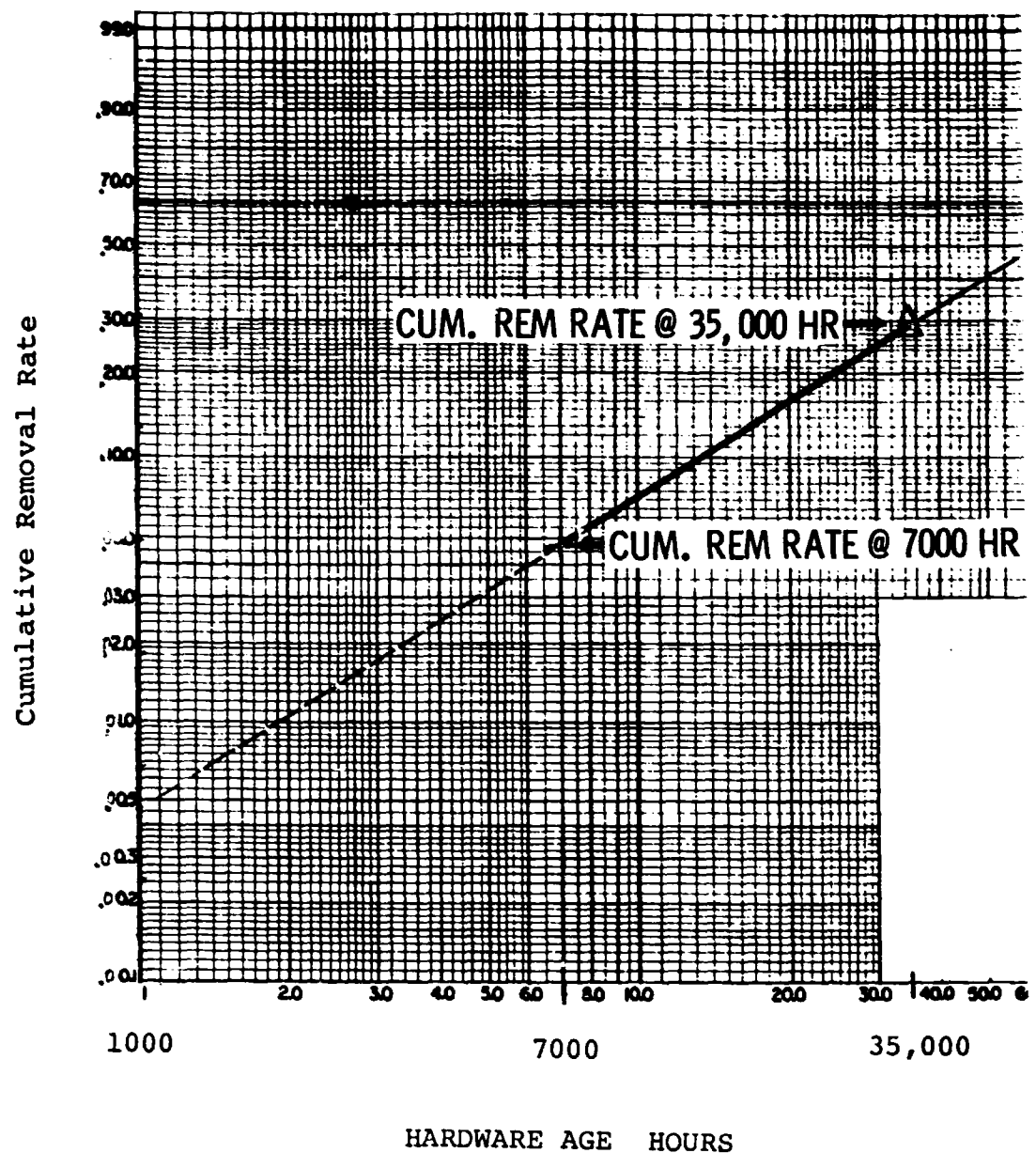


Figure 4.3.9.4.1-2. Extension of cumulative removal rate at 7000 hr. to 35,000 hr.

Some further reduction in the failure rate is expected due to the improved operating conditions afforded by use of helical gears and improved mounting and gear support. Dynamic loads and vibration influence bearing fatigue life as indicated by Reference 15. Improved alignment and concentricity and reduction of torsionals in the remaining accessory drive train will contribute to attainment of full calculated life at these locations. These factors however cannot be easily quantified to produce a further improved failure rate value.

A premature removal rate of 0.01 per 1000 hrs. was assumed for the accessory system within the main drive reduction gearbox. This assumption was based on the complexity of the accessory drive system being comparable to that of the main drive reduction system and that the same reliability design criteria would be used for the accessory drive gearbox as used for the main drive reduction gearbox. The accessory drive system gears and bearings will be designed for the same long life and high reliability as the main drive reduction gear system design was. As described in Section 4.3.3, these gears will be located between bearings on an integral shaft, thus affording better support than overhung or spline mounted gears. Positive lubrication will be provided.

More frequent internal inspection opportunities existed for the 501-D13 reduction gearbox than forecasted for the advanced main drive reduction gearbox. The 501-D13 reduction gearbox was disassembled for repair and inspection following premature or time removals. During the data base period the average gearbox was removed prematurely for repair between 0 and 7000 hr and then overhauled at 7000 hr average TBO period. During the inspections which were performed at the repairs and overhauls, distressed parts were replaced. With the "on condition" operation and the simplified, reliable gearbox there will not be the frequent replacement of parts. The effect may be a slight increase in the premature removal rate that was predicted solely from the improvement in the designs. An additional rate of 0.01 per 1000 hrs has been assumed for this effect. The inherent reliability predictions for the advanced main reduction gearbox are summarized in Table 4.3.9.4.1-I.

Table 4.3.9.4.1-I

Inherent Reliability Prediction Summary for
Advanced Main Drive Reduction Gearbox

| G/B system or reason | Inherent Premature removal rate per 1000 engine flight hrs for G/B system shown | | |
|---|--|---------------------------|----------------------------|
| | 501-D13 G/B @ 7,000 hr | Advance G/B @ 7,000 hr | Advance G/B @ 35,000 hr |
| Main reduction system only | 0.048* | 0.007 | 0.010 |
| Accy drives for 2 pumps and remote gearbox | NA** | NA | 0.010 |
| Effect of less frequent dis- assembly insp. | NA | NA | 0.010 |
| Total predicted for main G/B | NA | NA | 0.030 |
| Equivalent MTBR | NA | NA | 33,000 hr |

* From Table 3.5.2-II data for CY 1965-68 period

** NA = Not applicable

4.3.9.4.2 Non-inherent Reliability Assessments

Assessments for non-inherent causes were made similar to those made for the advanced propeller, as applicable, and as discussed previously in paragraph 4.3.9.3.2. The principle ones related to the main drive reduction gearbox are:

- Improper maintenance
- Unsubstantiated (no failure found)
- Accident damage

Foreign object damage is not a factor for the gearbox. Accident damage to the gearbox results from unusually large forces transferred to the gearbox from the propeller in case of an accident. The rate of accident damage removals plus precautionary removals following an accident are a function of the propeller accident rate. Thus the improved propeller accident rate discussed in paragraph 4.3.9.3.2.4 will have a corresponding favorable effect on this cause of non-inherent removal rates.

The non-inherent removal rates for improper maintenance and unsubstantiated causes were estimated from studying the historical data base and the relative complexity of the 501-D13 and the advanced gearbox. As for the Prop-Fan, the rate of improper maintenance will decrease in direct relation to the decreased rate of required maintenance actions.

The estimated non-inherent rate for the advanced main drive reduction gearbox is 1/3 of the inherent rate or 0.010/1000 hrs. As was done for the Prop-Fan, convenience removals charged to the gearbox are considered improper and therefore were not included.

4.3.9.5 Core Engine and LP Turbine

4.3.9.5.1 Inherent Reliability Assessment

The core engine and LP turbine are classified as major modules. Based on the reliability of current mature engines, the projected inherent reliability of the core is 6250 hours MTBR and of the LP turbine, 50,000 hours MTBR. The corresponding premature removal rates are 0.16/1000 hr and 0.02/hr respectively. These levels are comparable to those being demonstrated by the JT8D core and LP turbine.

The history of the 501-D13 experience during the data base period was studied from 2 important aspects:

- Whether reliability problems existed that were uniquely related to turboprop operation or application
- Identification of principal 501-D13 engine problems to evaluate solutions from present day or expected 1980 era technology.

No 501-D13 engine problems were identified as being unique to turboprop operations or application. Some of the 501-D13 problems resulted from the engine being originally designed and developed for much shorter life in military use and without comprehensive design criteria of today. Thus, one aspect of the core engine and LP turbine assessment recognizes the beneficial results of comprehensive design criteria which includes clearly stated reliability and life requirements for commercial operation.

The principal problems causing premature removal of the 501-D13 were identified along with the failure modes. These are shown in Table 4.3.9.5.1-I. The remarks shown relate to the specific 501-D13 problems shown.

Table 4.3.9.5.1-I
Principal 501-D13 Engine Inherent Failure Modes
Causing Unscheduled Replacement

| <u>Compressor Items</u> | <u>Modes</u> | <u>Remarks</u> |
|-------------------------|--|---|
| Front bearing oil seal | Carbon seal worn and chipped Seal follower carboned | Carbon seal replaced by a laby seal |
| Rear (Thurst) bearing | Separator breakage Rolling elements spalled | Continued improvements in sep. and mat'l. |
| Stage 1 vane | Fatigue breakage | Improved vibratory characteristics |
| Diffuser assembly | Oil delivery tube cracking | |

Table 4.3.9.5.1-I (Cont'd.)

| <u>Compressor Items</u> | <u>Modes</u> | <u>Remarks</u> |
|---|--|---|
| Diffuser scavenge oil pump (internal location) | Shaft and gear breakage | Removed to external position, combined with front turbine scavenge pump and driven from accessory drive |
| <u>Combustion Item</u> | <u>Modes</u> | <u>Remarks</u> |
| Combustion liner | Fatigue cracking at spot weld | Brazing at welds eliminated cracking |
| <u>Turbine Items</u> | <u>Modes</u> | <u>Remarks</u> |
| Stage 1 blades | Stress rupture and sulfidation of airfoil | Coatings and improved materials plus aircooling |
| Rear bearing support | Cracking of sheet metal sections | |
| Rear bearing | Separator breakage and rolling element wear and spalling | |
| Front bearing cage (Retainer) | Wear from bearing outer ring rotating | Locked outer ring |
| Front bearing scavenge pump (internal location) | Drive gear, bearing and shaft failures | Relocated external position, combined with diffuser scavenge pump and driven from accessory drive |

Some of the corrective actions are straight forward configuration and processing changes to better adapt to commercial maintenance plans and commercial overhaul periods. Others were based on improvements from technology and analytical improvement programs. Such programs have continued to provide industry-wide engine improvements since the time of principal 501-D13 changes. There is every reason to believe that this trend will continue to produce improved materials, coatings and analytical techniques available for the 1990 era IOC core engine.

4.3.5.2 Non-inherent Reliability Assessment

An assessment of .040 removals per 1000 hrs was made for the core engine. The causes of those would be expected to be FOD to the compressor, improper maintenance and operation and unsubstantiation (no fault found). With the fault diagnostic systems envisioned and the beneficial effect on improper maintenance due to a lower maintenance action rate, the estimate of 0.040 seems reasonable at this time.

4.3.9.6 Power Section Accessory Gearbox, Components and Accessories

4.3.9.6.1 Inherent Reliability Assessment

The basis for the reliability assessments of power section accessories were detailed studies made for the XT701 engine (most in conjunction with the suppliers), history of the 501 including the more recent Series III (501-D22 and the T56-A-14 and 15), and DDA/supplier estimates for electronic control systems. The estimates by general functional group are shown in Table 4.3.9.2-II.

4.3.9.6.2 Non-inherent Reliability Assessment

Estimates were made for component and accessory removal rates for non-inherent causes using the same background data, studies and supplier experience as discussed for the inherent reliability assessment (4.3.9.6.1). These rates were also included in Table 4.3.9.2-II.

4.3.9.7 Comparison of Projected Advanced Turboprop and Current Turboprop Reliability

The total projected equipment operational removal rate for the advanced turboprop propulsion system is shown in Figure 4.3.9.7-1 as compared to the corresponding baseline 501-D13/54H60 turboprop system. The total removal rate consists of major module, component and accessory rates. The 1990 era turboprop rates were projected for the 1.25 hours per flight. The baseline 501-D13/54H60 rates are for the Electra 0.8 hours per flight. The corresponding value adjusted for the effects of 1.25 hours per flight rather than 0.8 hours per flight would show a 10-12% improvement.

The projected removal rates shown in Figure 4.3.9.7-1 for the advanced turboprop system at maturity are 50% of those of the 1960 era baseline turboprop (unadjusted for the hours per flight differences). The comparison of the major module removal rates shows a more dramatic improvement which is the result of the modular concept. This is shown in Figure 4.3.9.7-2 along with some key comments related to the improvements of the subsystems which are discussed in the text.

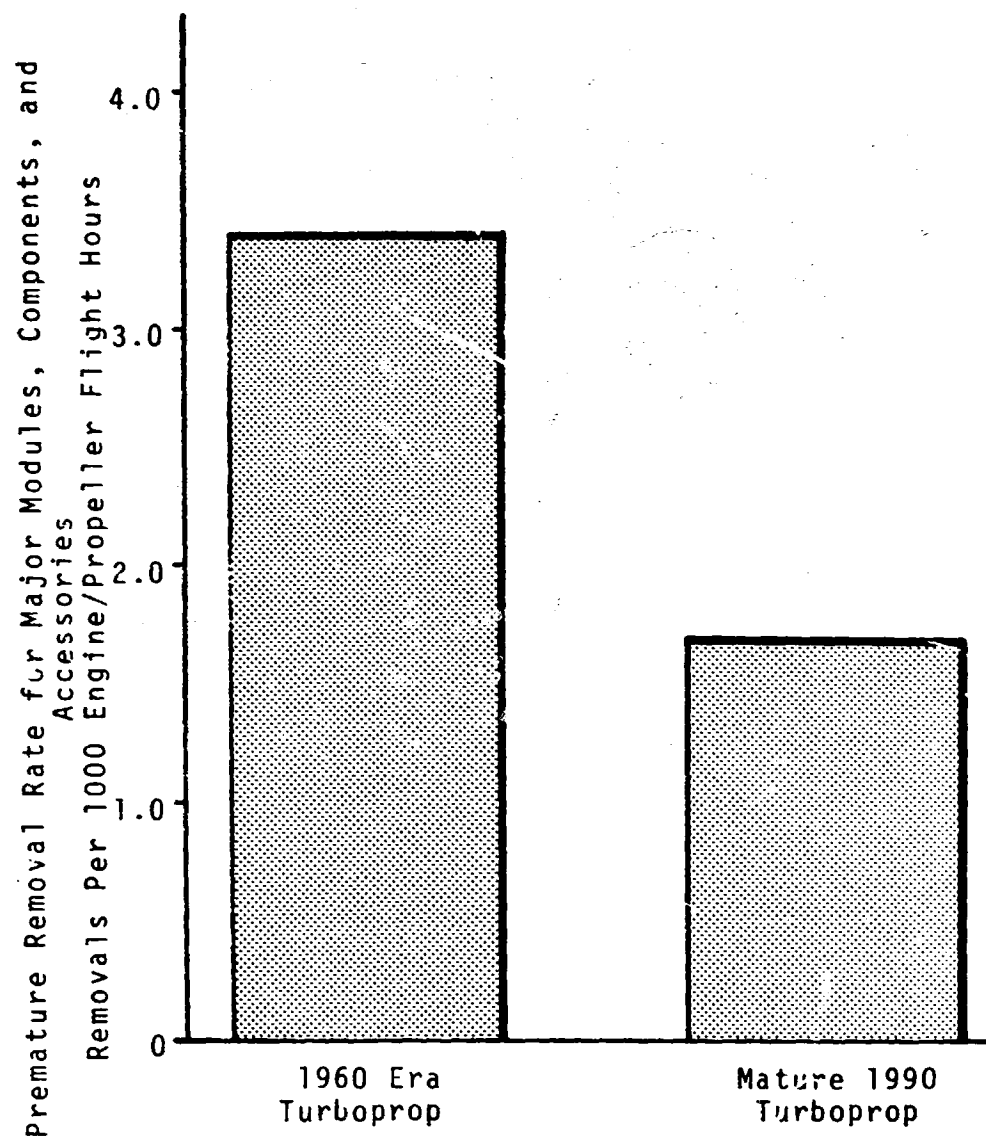


Figure 4.3.9.7-1 Projected total propulsion system equipment operational reliability for advanced turboprop.

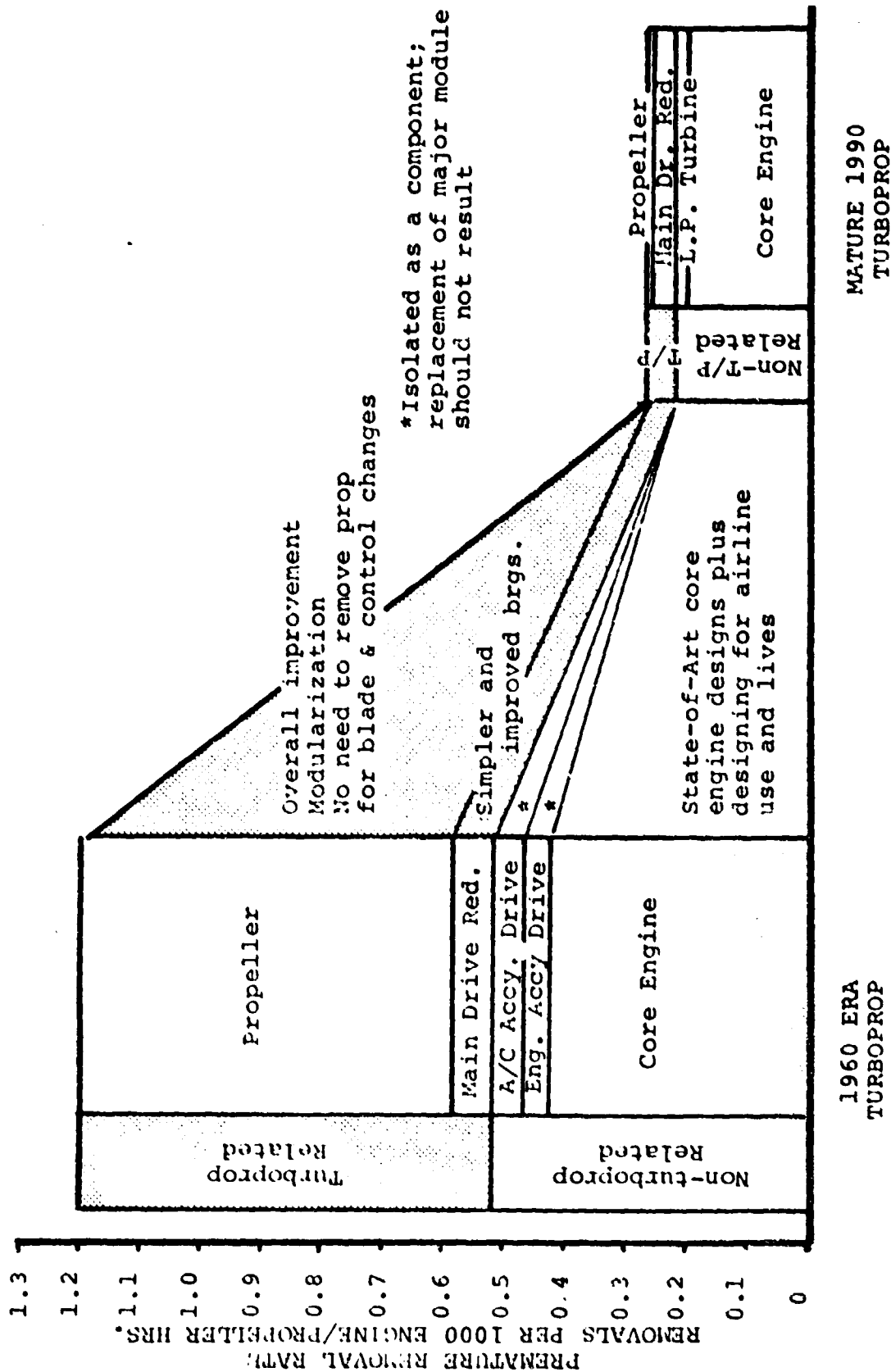


Figure 4.3.9.7-2. Projected major module operational reliability for advanced turboprop.

4.4

Maintenance Cost Projection of Future System

The maintenance cost projections for the advanced turboprop propulsion system were estimated by multiplying the line and shop labor and material charges per maintenance action by the corresponding rate of maintenance action, or repairs. The results are presented in Table 4.4-I. Labor charges were based on data presented in Section 4.3.8 and maintenance action frequency, or repair rates, were based upon data presented in Section 4.3.9. Labor costs expressed in CY 1976 dollars were based on a direct labor rate of \$9.00 per hour and a burden labor rate of \$27.00 per hour.

Material costs per repair were developed using estimated acquisition costs and historical data relating per repair material costs to acquisition costs on a percentage basis. The power section, main drive reduction gearbox, accessories, and control system acquisition costs were developed by the DDA Value Engineering Department based on an analysis of the hardware as defined on the concept drawings, the developed parts list, the actual costs of T701 parts, and with the assistance of the production cost estimating department. The Prop-Fan acquisition costs were developed by the Cost Engineering group of HS Aircraft Systems Department based on analysis of the hardware as defined on the concept drawings and the developed parts list. The analyses use standard techniques for estimating production hardware costs including comparisons with costs for similar parts currently in production.

Per repair material costs as a percentage of acquisition costs for the power section, main drive reduction gearbox, accessories, and control system were established by the DDA Maintainability Department based upon the data collected from Eastern Airlines (Section 3.2.3.3.1), the repair facilities (Section 3.2.4.1), and in-house data on other engines. The effects of "on-condition" maintenance, condition monitoring, and incorporation of modifications and service bulletins with repair instead of overhauls were also included.

Per repair material costs as a percentage of acquisition cost for the Prop-Fan were established based on the Saturn Airways 54H60 propeller experience. Repair and overhaul material costs for the L-382 (reference Table 3.2.2.2-III) were converted to percentages of acquisition cost. The median of the respective component overhaul and repair percentages was established. These percentages were applied to the comparable Prop-Fan component acquisition costs to establish average repair costs. A percentage based on the average of 54H60 overhaul and repair costs expressed as a percentage was used for the following reasons:

- Elimination of scheduled overhauls will result in the incorporation of Prop-Fan modifications and service bulletins during repairs causing average repair costs expressed as a percentage of acquisition cost to be more comparable with 54H60 overhaul costs (rather than 54H60 repair costs) expressed as a percentage of acquisition cost.
- Hardware simplification and improved durability should result in Prop-Fan per repair material costs expressed as a percentage of acquisition cost to be lower than the per overhaul costs for comparable 54H60 propeller hardware.

The data from Table 4.4-I is plotted in bar chart form on Figure 4.4-1 and compared with the JT8D. Comparisons were made on the basis of a duty cycle of 0.8 per engine flight hour as described in Appendix A. The JT8D costs were taken from B727-100 operation by the domestic trunk airlines as described in Section 3.4. Both propulsion systems are therefore performing the same mission. These comparisons are made between a relatively old technology but widely used turbofan and a new technology turboprop. The comparison indicates that the advanced turboprop will be less expensive to maintain than the JT8D. However, corresponding improvements can also be achieved for a turbofan and a comparison with an advanced turbofan is made in Section 4.4.1. It should be noted that dramatic maintenance cost reductions have been made in the turboprop system, reference Figure 3.4.3-1, and they are explained in Section 4.4.3. It should be noted from Figure 4.4-1 that the propeller and gearbox costs of the turboprop system can be made quite competitive with the fan and reverser costs of the turbofan, which are the essential differences between a turboprop and turbofan system for comparable technology engines.

Table 4.4-I
Summary of Advanced Turboprop Propulsion System Maintenance Cost Per Flight Hour

| Item and Maintenance Action | Maintenance Actions Per 1000 Flight Hours | | Shop Manhours Per Repair | Line Manhours Per Repair | Parts Cost Per Repair | MMH(4) Per 1000 FH | Labor \$(1) Per 1000 FH | PC(5) Per 1000 FH | Total \$(1) Per 1000 FH |
|-----------------------------------|--|--|--------------------------------|--------------------------------|-----------------------------|--------------------------|-------------------------------|-------------------------|-------------------------------|
| | | | | | | | | | |
| Advanced Propeller | | | | | | | | | |
| Spinner Repair | 0.0086 | | 25.0 | 0.2 | 500 | 0.217 | \$ 1.950 | \$ 4.300 | \$ 6.250 |
| Disc & Aft Fairing Repair | 0.0029 | | 8.0 | 4.0 | 1,750 | 0.035 | 0.315 | 5.075 | 5.390 |
| Pitch Change Actuator Repair | 0.0332 | | 22.4 | 4.4 | 1,625 | 0.890 | 8.010 | 53.950 | 61.960 |
| Blades Repair | 0.0459 | | 45.4(3) | 2.3(3) | 7,075 | 2.189 | 19.705 | 324.743 | 344.448 |
| Forward Cover & Fairing Repair | 0.0055 | | 7.5 | 1.3 | 250 | 0.048 | 0.436 | 1.375 | 1.811 |
| Pitch Change Regulator Repair | 0.0912 | | 48.9 | 2.8 | 1,000 | 4.715 | 42.435 | 91.200 | 133.635 |
| Components Repair | 0.1756 | | 8.0 | 1.0 | 250 | 1.580 | 14.220 | 43.900 | 58.120 |
| Subtotals | | | | | | 9.674 | \$ 87.071 | \$524.543 | \$611.614 |
| Subtotals (2) | | | | | | 9.674 | \$261.213 | \$524.543 | \$785.756 |

- (1) Based on unburdened labor rate of \$9.00 per hour
(2) Based on burdened labor rate of \$27.00 per hour
(3) Based on assumption that typical incident causing blade damage will result in two blades requiring repair.
(4) Maintenance man-hours
(5) Parts cost

Table 4.4-I (cont.)

Summary of Advanced Turboprop Propulsion System Maintenance Cost Per Flight Hour

| Item and Maintenance Action | Maintenance Actions Per 1000 Flight Hour | Shop Manhours Per Repair | Line Manhours Per Repair | Parts Cost Per Repair | MMH Per 1000 FH | Labor \$(1) Per 1000 FH | PC Per 1000 FH | Total \$(1) Per 1000 FH |
|---|--|--------------------------|--------------------------|-----------------------|-----------------|-------------------------|----------------|-------------------------|
| | | | | | | | | |
| Main Drive Reduction Gearbox | | | | | | | | |
| Major Repair | 0.004 | 168.0 | 12.0 | 9,380 | 0.720 | \$ 6.48 | \$ 37.52 | \$ 44.00 |
| Minor Repair | 0.036 | 78.0 | 12.0 | 1,190 | 3.240 | 29.16 | 42.84 | 72.00 |
| Subtotals | | | | | 3.960 | \$ 35.64 | \$ 80.36 | \$ 116.00 |
| Subtotals(2) | | | | | 3.960 | \$106.92 | \$ 80.36 | \$ 187.28 |
| Power Section, Accessories, Line Inspection | | | | | | | | |
| Power Section | | | | | | | | |
| Major Repair | 0.006 | 1689.5 | 10.5 | 200,700 | 10.200 | \$ 91.80 | \$1204.20 | \$1296.00 |
| Gas Generator | | | | | | | | |
| Compressor Repair | 0.097 | 789.8 | 10.2 | 38,800 | 77.600 | 698.40 | 3763.60 | 4462.00 |
| HP Turbine/Combustor | 0.050 | 39.8 | 10.2 | 73,550 | 2.500 | 22.50 | 3677.50 | 3700.00 |
| ● Scheduled Blade Replacement | 0.097 | 64.8 | 10.2 | 29,225 | 7.275 | 65.48 | 2834.83 | 2900.31 |
| ● Repair | | | | | | | | |
| Power Turbine Repair | 0.020 | 134.0 | 6.0 | 23,740 | 2.800 | 25.20 | 474.80 | 500.00 |
| Engine Accessory Gearbox Repair | 0.025 | 99.7 | 0.3 | 600 | 2.500 | 22.50 | 15.00 | 37.50 |
| Engine Accessories Repair (average) | 0.036 | 24.7 | 0.3 | 775 | 0.900 | 8.10 | 27.90 | 36.00 |
| Engine Minor Components Repair (average) | 0.200 | 7.8 | 0.2 | 428 | 1.600 | 14.40 | 85.60 | 100.00 |
| Starting System Repair | 0.333 | 19.7 | 0.3 | 2,820 | 6.660 | 59.95 | 939.06 | 999.00 |
| Electronics & Controls Repair | 0.500 | 23.5 | 0.5 | 784 | 12.000 | 108.00 | 392.00 | 500.00 |
| Line Inspections | | | | | 125.556 | 1130.00 | -- | 1130.00 |
| Subtotals | | | | | 249.591 | \$2,246.33 | \$13,414.49 | \$15,660.82 |
| Subtotals(2) | | | | | 249.591 | \$6,738.96 | \$13,414.49 | \$20,153.45 |

Table 4.4-I (cont.)

Summary of Advanced Turboprop Propulsion System Maintenance Cost Per Flight Hour

| Item and Maintenance Action | Maintenance Actions Per 1000 Flight Hours | | Shop Manhours Per Repair | | Line Manhours Per Repair | | Parts Cost Per Repair | | MMH Per 1000 FH | | Labor \$(1) Per 1000 FH | | PC Per 1000 FH | | Total \$(1) Per 1000 FH | |
|--|--|--|--------------------------------|--|--------------------------------|--|-----------------------------|--|-----------------------|--|-------------------------------|--|----------------------|--|-------------------------------|--|
| | | | | | | | | | | | | | | | | |
| <u>Grand Totals (Direct)</u> | | | | | | | | | | | | | | | | |
| Advanced Propeller | | | | | | | | | | | | | | | | |
| Main Drive Reduction Gearbox | | | | | | | | | | | | | | | | |
| Power Section, Accessories, Line Inspections | | | | | | | | | | | | | | | | |
| Totals | | | | | | | | | | | | | | | | |
| <u>Grand Totals (Burdened)</u> | | | | | | | | | | | | | | | | |
| Advanced Propeller | | | | | | | | | | | | | | | | |
| Main Drive Reduction Gearbox | | | | | | | | | | | | | | | | |
| Power Section, Accessories, Line Inspections | | | | | | | | | | | | | | | | |
| Totals | | | | | | | | | | | | | | | | |

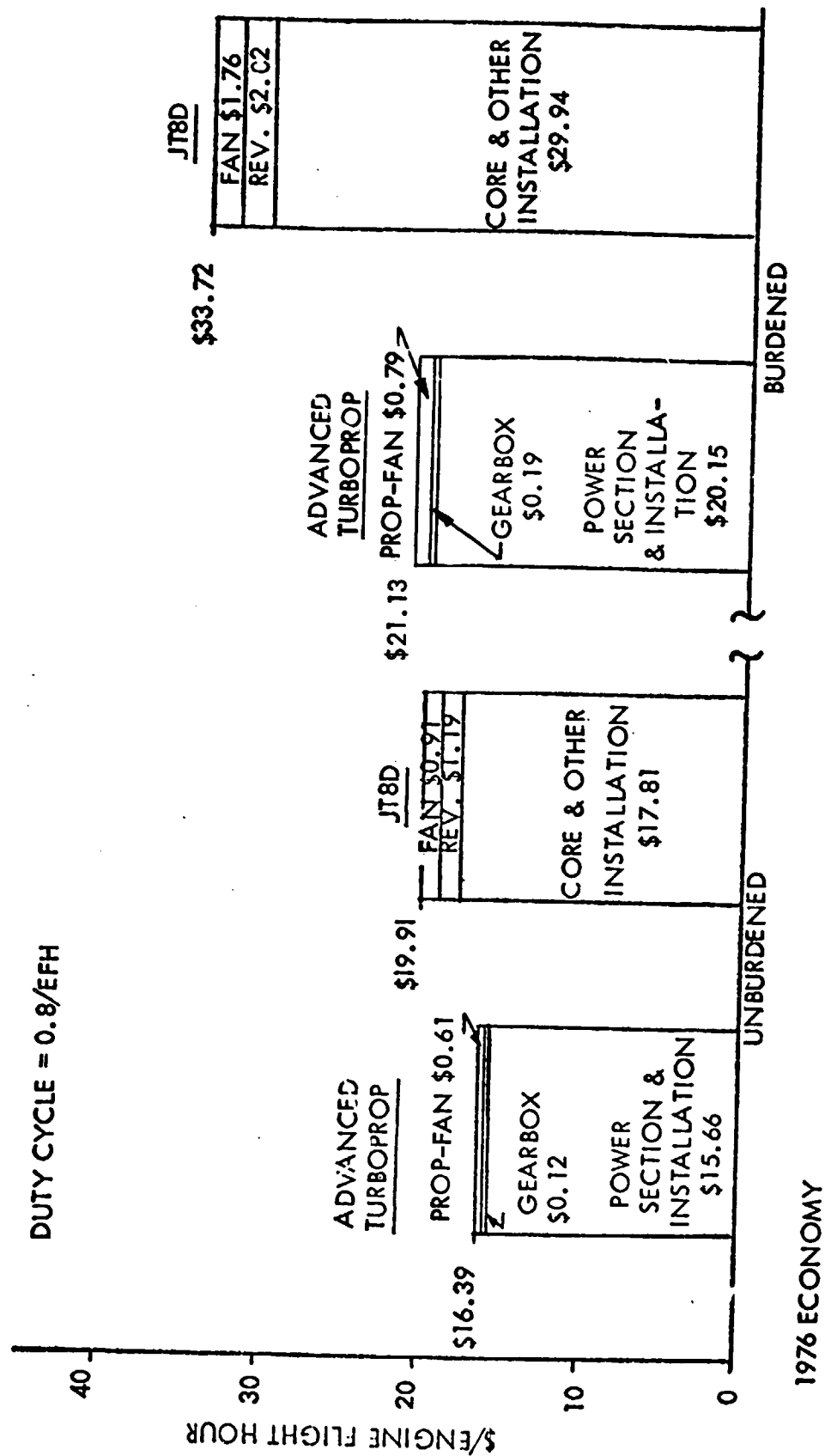


Figure 4.4-1. Advanced turboprop maintenance cost projection.

4.4.1 Advanced Turboprop Comparison with an Advanced Turbofan

A comparison was also made of the projected maintenance costs of the advanced turboprop system with those of an advanced turbofan. The advanced turbofan costs were estimated using the engine maintenance direct cost formulae in the 1967 ATA (American Transport Association) "Standard Method of Estimating Comparative Direct Operating Costs of Turbine Powered Transport Airplanes", as modified by General Electric in Reference 14.

A turbofan engine SLS thrust of 14,000 lbs. was assumed, as that represented an equivalent turbofan system to the advanced turboprop system of this study, as discussed in Section 4.2. Maintenance costs for turbofan engine prices varying from \$400,000 to \$1,200,000 were calculated and are shown in Figure 4.4.1-1. An engine price of \$600,000 in CY 1976 dollars was estimated as representing an advanced turbofan of 14,000 lbs SLS thrust at production quantities and rates representing the time period of a mature engine. From Figure 4.4.1-1 the corresponding maintenance cost is \$17.71 per engine flight hour. This cost was further broken into a fan cost of \$1.31 and a reverser cost of \$1.09, with the remainder of \$15.31 for the core and other installation costs.

A comparison of the advanced turboprop and the advanced turbofan is shown in Figure 4.4.1-2. The comparison shows that the power section and installation costs of the turboprop is comparable to the projected core and other installation costs of the advanced turbofan. As explained in other sections of this report it would be expected that the turboprop core will be less than the turbofan core. The interesting comparison is the sum of the Prop-Fan and reduction gear costs, \$0.73 and \$0.98, versus the sum of the fan and reverser costs \$2.40 and \$4.16.

The conclusion from this comparison is that advanced turboprops and advanced turbofans, using similar cores, will have very competitive maintenance costs per flight hour.

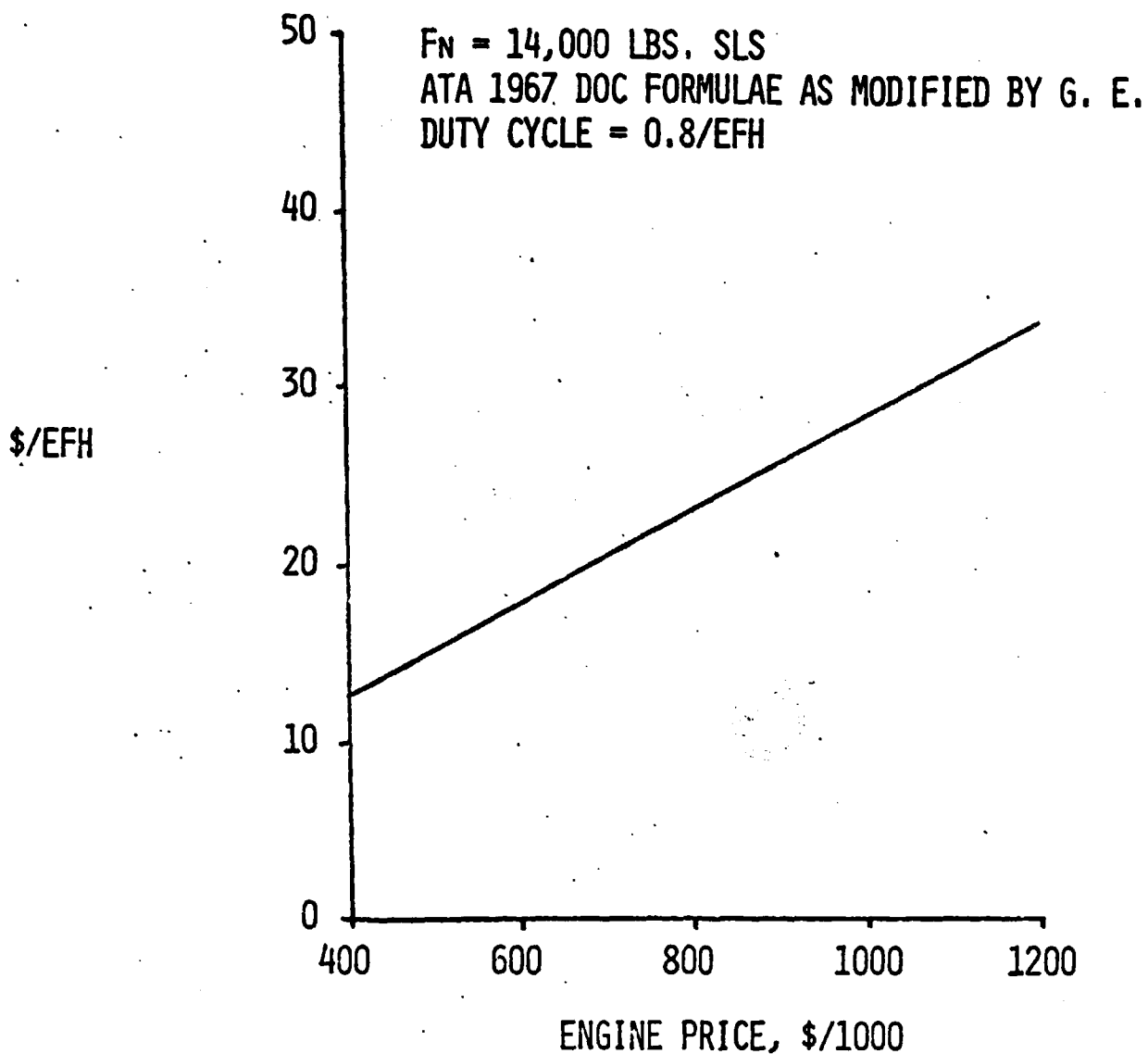


Figure 4.4.1-1. Variation of estimated advanced turbofan maintenance costs with engine price.

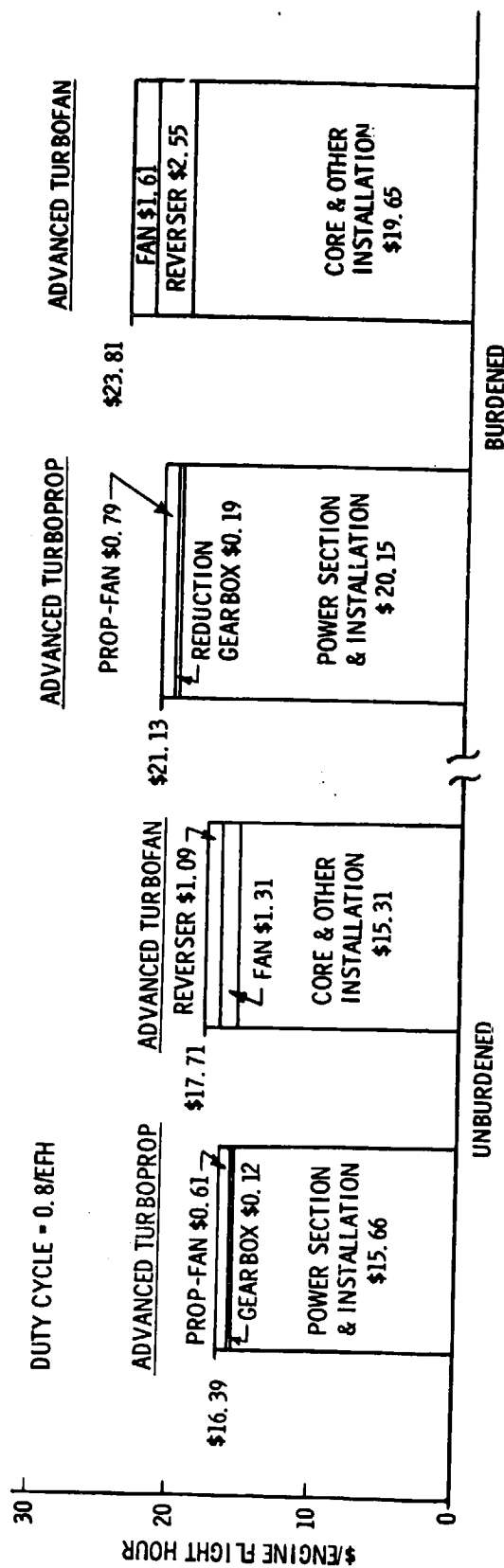


Figure 4.4.1-2. Advanced turboprop and advanced turbofan maintenance cost comparison.

4.4.2 Direct Operating Cost (DOC) Sensitivity to Propulsion System Maintenance Costs

The recent RECAT (Reduced Energy Consumption for Commercial Air Transport) studies reported in References 2, 10, 11, 12, and 13 present an insight to the sensitivity of DOC to propulsion system maintenance. Reference 13 shows that in United Airlines operation of B737-200 aircraft over trip distances of 500 nautical miles, the fully burdened engine maintenance cost is approximately 8% of the DOC of the aircraft. Thus a 50% increase in engine maintenance cost would result in a 4% increase in DOC.

When considering the advanced turboprop system versus the advanced turbofan where the primary question is the cost of the advanced propeller and reduction gearbox, assuming the core costs are approximately equal, Figure 4.4.2-1 shows the sensitivity of advanced propeller and gearbox maintenance costs on DOC. The data is based upon References 2, 10, 11, and 12 and the maintenance cost information projected for those studies. Figure 4.4.2-1 shows that doubling those projected advanced propeller and reduction gear maintenance costs reduced the turboprop improvement for DOC by less than 1%. This leads to the important conclusion that even if estimated advanced turboprop maintenance costs are low by as much as a factor of two, the advanced turboprop propulsion system still offers nearly a 5% advantage in DOC over comparable turbofans.

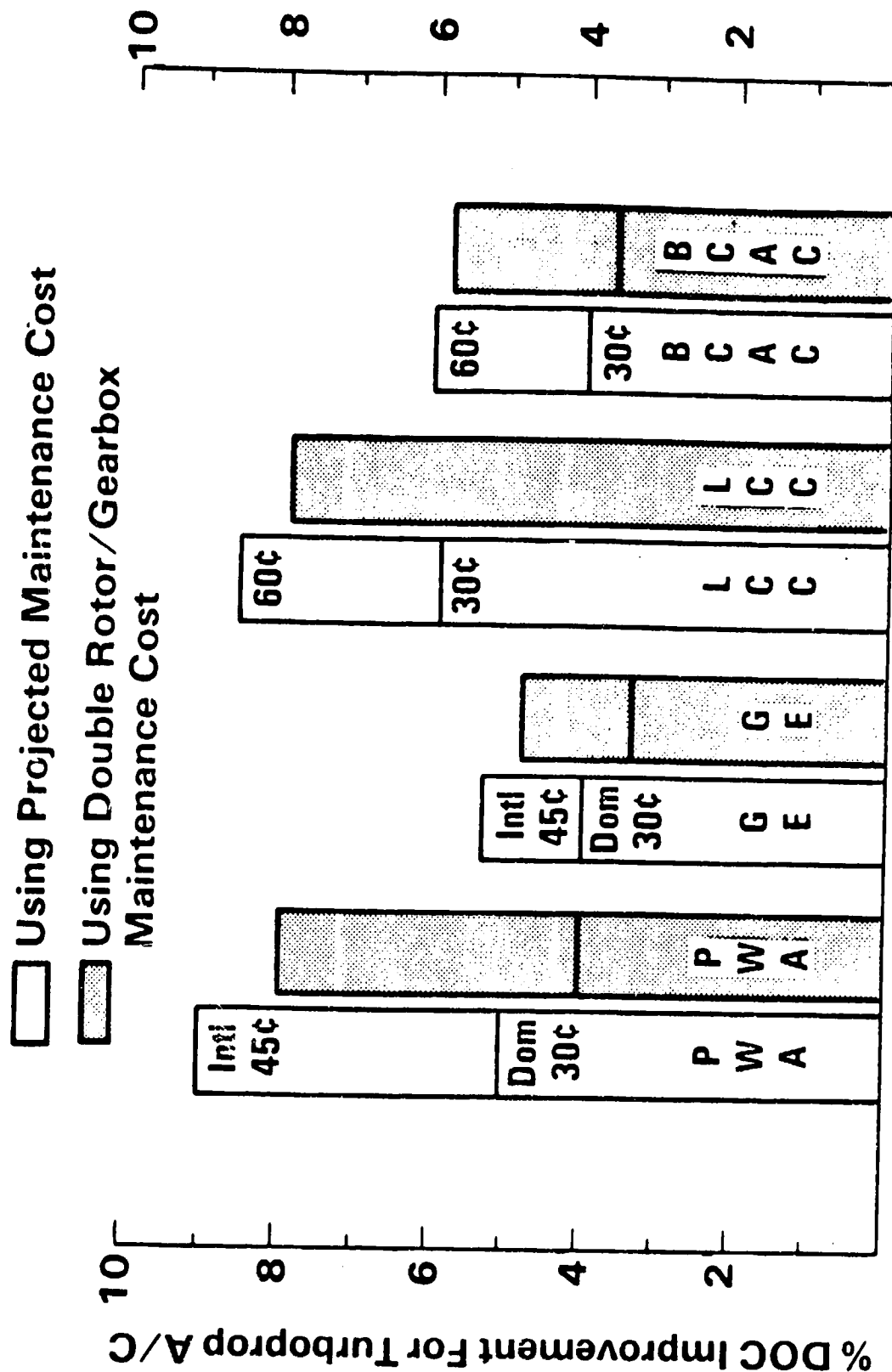


Figure 4.4.2-1. DOC Sensitivity to Prop-Fan Maintenance Costs.

4.4.3 Quantification of Benefits

A detailed comparison is made in this section of the maintenance cost per flight hours of the 501-D13/54H60 system versus the advanced turboprop system. The comparison is made on the basis of unburdened costs which eliminates the question of burdening rates. The results shown and discussed in this section quantify the benefits of the improvements that are proposed for the advanced turboprop system.

4.4.3.1 Prop-Fan

The HS 54H60 propeller fully burdened shop maintenance cost of \$2.36 based on Saturn L-382 experience (Reference Table 3.3.2.2-III) was unburdened resulting in a value of \$1.65 per propeller hour. This figure was adjusted to reflect the Prop-Fan duty cycle of 1.25 hours per flight as used in this study, the addition of line maintenance, and scaling to reflect the Prop-Fan propulsor size. These adjustments result in an unburdened maintenance cost of \$2.26 per propeller flight hour for a propeller of 54H60 complexity, sized for a rating equivalent to the Prop-Fan designed for this study and flown at the assumed duty cycle of 1.25 hours per flight.

Figure 4.4.3.1-1 graphically shows how this maintenance cost is reduced to a value of \$0.61 per flight hour as projected for Prop-Fan, and is discussed below:

- Avoidance of scheduled maintenance eliminates 50.4% of the maintenance cost. This assumes the design philosophy of on-condition maintenance for Prop-Fan will be such that all scheduled maintenance will be avoided and that this can be depicted graphically by showing the elimination of 54H60 scheduled maintenance costs.
- More durable heaters designed for Prop-Fan will result in a reduction of heater costs which is equivalent to 6.2% of the total maintenance cost. This includes consideration of the fact there are 4 heaters per 54H60 propeller versus 8 per Prop-Fan.
- The balance of the cost reduction is a result of the combined effects of improved reliability (other than blade heaters), modularity and hardware simplification which results in lower costs per repair, and improved diagnostics. One specific example of hardware simplification is the propeller control. Current propeller controls are complex hydro-mechanical devices. A FADEC has been proposed for Prop-Fan.

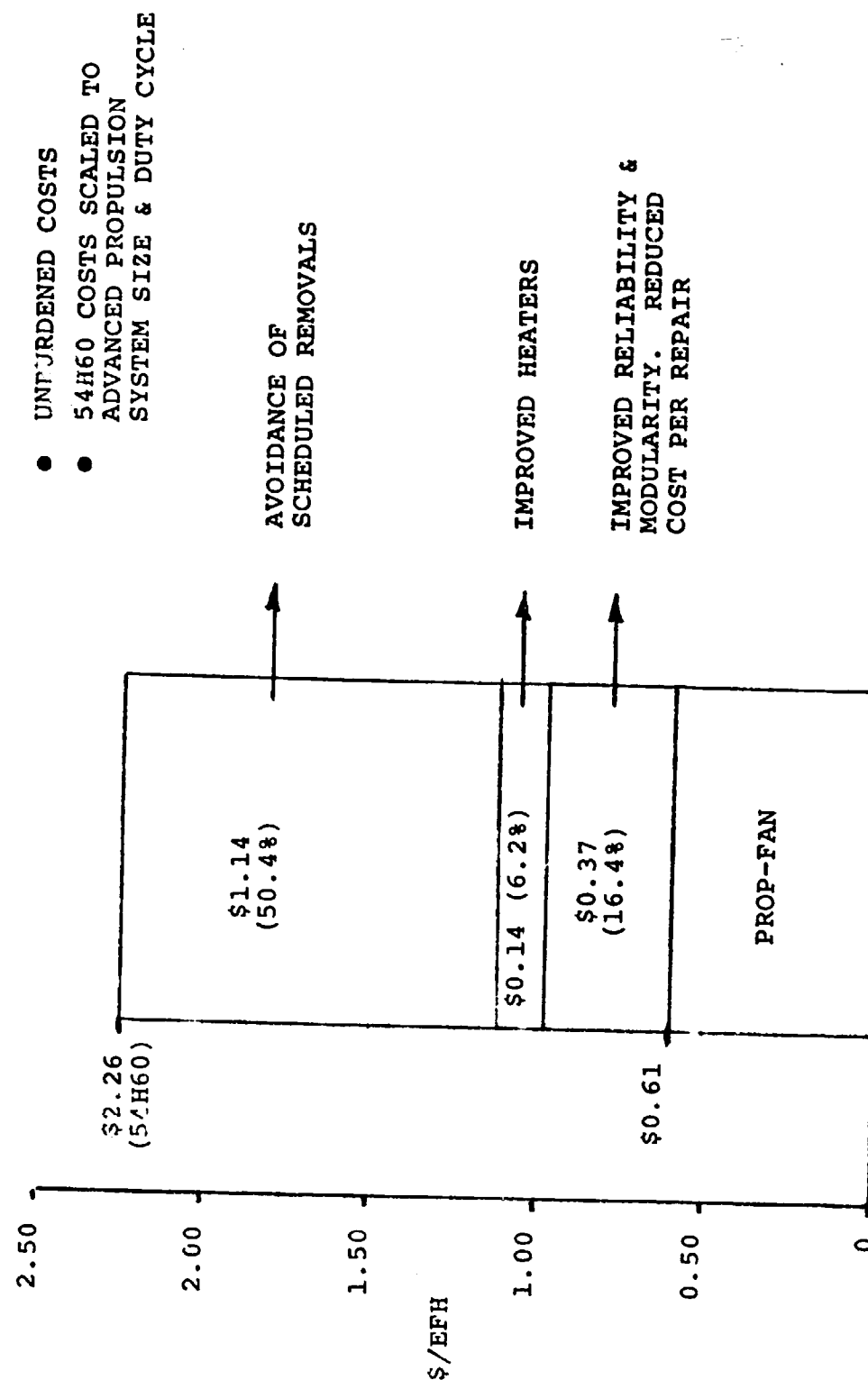


Figure 4.4.3.1-1. Maintenance Cost Reduction Sources for Prop-Fan

In summary, improved reliability including blade heaters, modularity and hardware simplification, and improved diagnostics account for 22.6% of the reduction in maintenance cost.

4.4.3.2 Main Drive Reduction Gearbox

The unburdened 501-D13 reduction gear maintenance cost of \$1.94 shown in Figure 3.3.3-1 was adjusted to reflect the scaling required to the advanced turboprop propulsion system size, as discussed in Sections 3.4.2 and 4.2. These adjustments resulted in a reduction gear maintenance cost of \$2.32 per engine flight hour.

Figure 4.4.3.2-1 graphically shows how the \$2.32 is reduced to \$0.12 for the advanced system.

- Avoidance of scheduled removals/overhauls eliminates 58.6% of the maintenance cost. This assumes that for the design philosophy of on-condition maintenance all scheduled maintenance will be avoided and that this can be depicted graphically by showing the elimination of the 501-D13 scheduled maintenance costs of \$1.36/EFH.
- Aircraft, engine, and propeller accessory drives accounted for 43.3% of the 501-D13 reduction gear maintenance. In the advanced system all aircraft accessory drives have been eliminated from the reduction gearbox, but substituted by one drive to an aircraft mounted aircraft accessory gearbox. Reduction gear mounted engine accessories were either eliminated or moved to the power section accessory drive. The only remaining accessory drives are for pressure and scavenge pumps of the gearbox and propeller. These changes removed 18.5% of the 501-D13 maintenance cost, or \$0.43/EFH.
- The compound idler system of the advanced gearbox was estimated to be much cheaper to manufacture than a planetary system similar to the 501-D13. This was due to a simpler system with fewer parts. The relative cost reduction was 37%. This results in a further 9.2% reduction in maintenance cost, or \$0.22/EFH.
- The balance of the cost reduction, \$0.19/EFH or 8.2% is a result of the combined effects of improved reliability, modularity and improved diagnostics resulting in lower cost per repair, and fewer non-inherent removals.

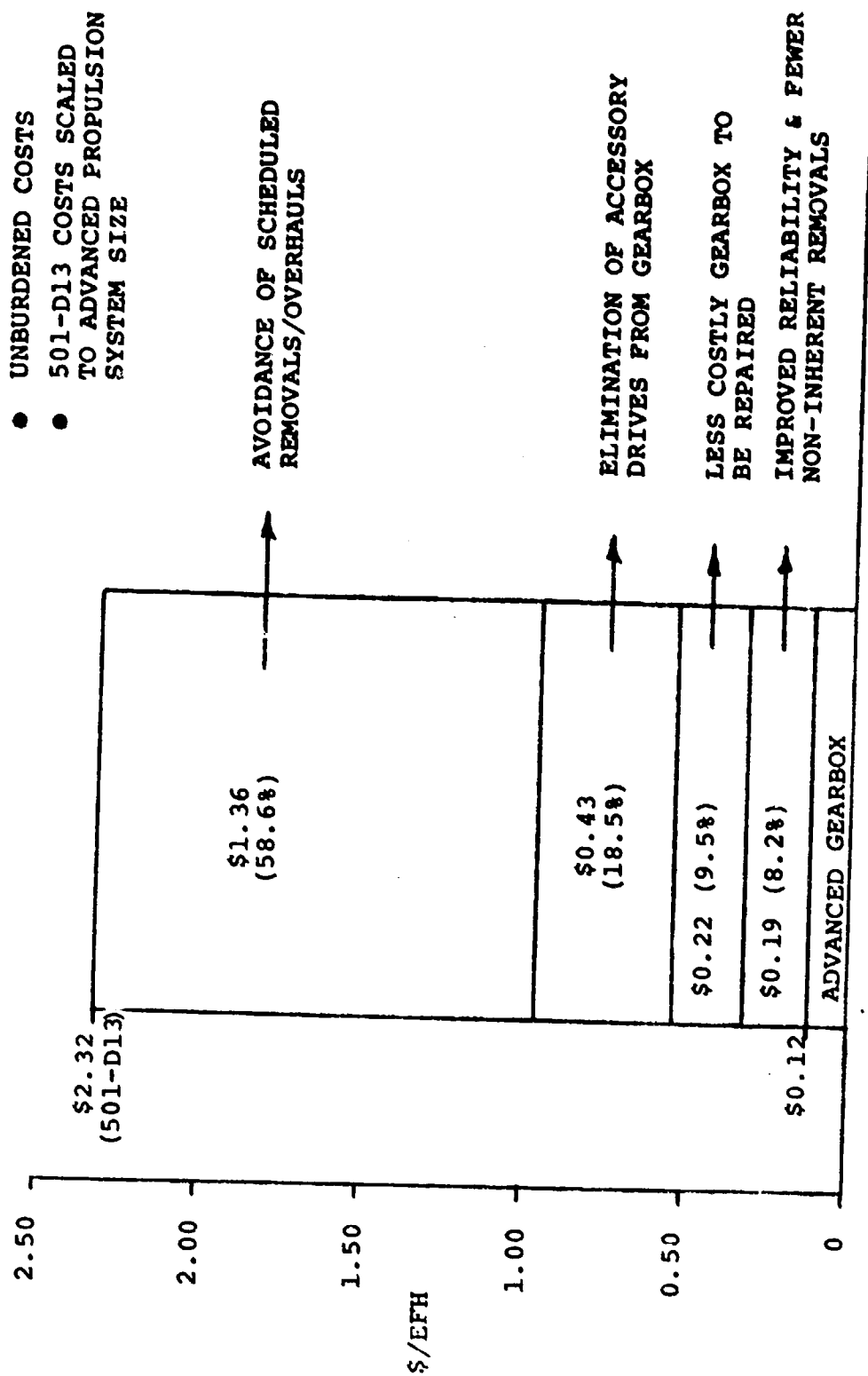


Figure 4.4.3.2-1. Maintenance Cost Reduction Sources for Advanced Reduction Gearbox

4.4.3.3 Core Engine and Installation

The unburdened 501-D13 engine and installation maintenance costs of \$17.66 shown in Figure 3.3.3-1 were adjusted to reflect the scaling required to the advanced turboprop propulsion system size, as discussed in Section 3.4.2 and 4.2. These adjustments resulted in an engine and installation maintenance cost of \$24.74 per engine flight hour.

Figure 4.4.3.3-1 graphically shows the comparison of costs of the 501-D13 with the advanced turboprop core.

- Avoidance of scheduled removals/overhauls eliminates 39.6% of the 501-D13 maintenance cost. This assumes that for the design philosophy of on-condition maintenance all scheduled maintenance will be avoided and that this can be depicted graphically by showing the elimination of the 501-D13 scheduled maintenance costs of \$9.79.
- The remainder of \$14.95 is the cost of unscheduled maintenance plus line maintenance for the 501-D13. The corresponding cost for the advanced core is \$15.66, which is slightly higher than that of the 501-D13. The cost of the advanced core does include costs for scheduled blade replacement in the HP turbine every 20,000 engine flight hours. Costs for the advanced core are detailed in Table 4.4-I, and line inspection costs were apportioned to the components. Non-inherent removal rates were included in the advanced core component rates in determining component costs. The results show that each component of the advanced core will be more expensive to maintain than the 501-D13. This is a result of a combination of a more expensive higher technology engine but offset to some extent by two things:
 - a. improved reliability.
 - b. relatively lower costs per repair because of improved diagnostics that allows detection of failure onset prior to major failure.

In summary, the combined effects of eliminating scheduled maintenance, except for HP turbine blades, improved reliability, lower cost per repair due to improved diagnostics, but a higher technology higher priced engine, results in a core maintenance cost per flight hour slightly higher than the existing 501-D13. The dramatic but viable reductions in Prop-Fan and advanced reduction gear costs, coupled with the core costs results in an overall propulsion system cost that is very comparable to projected advanced turbofan costs.

- UNBURDENED COSTS
- 501-D13 COSTS SCALED TO ADVANCED PROPULSION SYSTEM SIZE

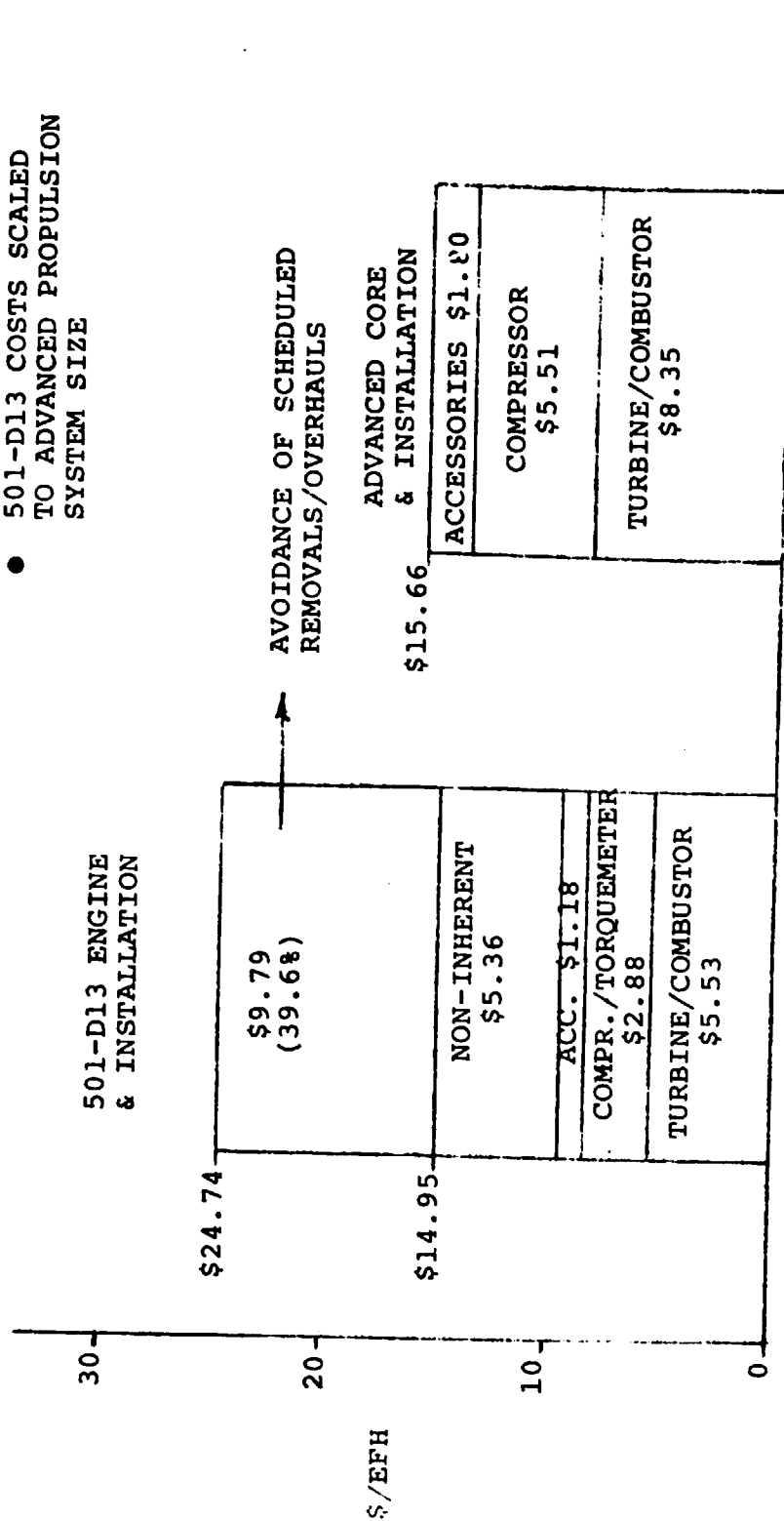


Figure 4.4.3.3-1. Maintenance Cost Reduction Sources for and Comparison with Advanced Core

5.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE TECHNOLOGY DEVELOPMENT

This study of turboprop systems reliability and maintenance costs was conducted to achieve the following objectives:

- to identify and understand the overall and relative reliability and maintenance costs (R&MC's) of the power section, gearbox, propeller, and accessories of past and current turboprop systems.
- to quantitatively project the R&MC improvements that could reasonably be expected to occur from these levels to those of new turboprop systems of the 1985 - 1990 IOC time period.

5.1 Conclusions

The real era of turboprop usage by the domestic airlines was in the early to mid 1960's. The DDA 501-D13 engine with either Aeroproducts 606 or Hamilton Standard 54H60 propellers was the largest and most widely used system. The engine, gearbox, and propellers of this system were adaptations of military designs of the 1950's. They were designed on the basis of a scheduled overhaul philosophy. For the airlines these scheduled overhauls were gradually increased from 4000 up to 9000 hours (TBO's) during the mature period of operation of the 501-D13. In comparison with the JT8D, the second generation turbofan in airline use and of later technology than the 501-D13, the maintenance cost of the turboprop was high in comparison to the turbofan. It was found, after adjusting for propulsion system size and for duty cycle, that the maintenance cost per flight hour of the older generation turboprop was 75% worse than that of the JT8D.

The maintenance cost drivers in the turboprop system were as follows:

Engine and Gearbox

| | |
|---------------------------|-------|
| ● Scheduled removals | 41.4% |
| ● Premature removals | 58.6% |
| ● Turbine | 20.0% |
| ● Non-inherent | 19.5% |
| ● Compressor | 10.4% |
| ● Engine Accessories | 4.3% |
| ● Reduction gearbox | 4.2% |
| ● Combustor & Torquemeter | 0.2% |

Propeller

| | |
|---|-------|
| ● Scheduled removals | 39.5% |
| ● Premature removals | 60.5% |
| ● Heaters | 31.7% |
| ● Misc. Control and Valve Housing Repairs | 10.3% |
| ● Misc. Prop. Assy Repairs | 9.1% |
| ● Misc. Component Repairs | 6.9% |
| ● Accident (FOD) | 2.5% |

The study of past and current turboprop systems clearly indicated that an advanced turboprop propulsion system for the 1990 era should incorporate the following features:

- On-Condition Maintenance Concept - A design objective of any future system must be the achievement of On-Condition maintenance whereby scheduled overhauls are eliminated and inspections are minimized. This alone has the potential of eliminating 40 percent of the current engine, reduction gear, and propeller maintenance cost. A condition which will facilitate the implementation of this maintenance concept in commercial aircraft service is improved fault detection and isolation via diagnostics to identify impending problems such that corrective action can be taken prior to failure.

A clearly defined on-condition maintenance concept must be developed in conjunction with potential user airlines and the aircraft designers. These concepts would take into account maintenance access times, likely available skill levels and support equipment. Thus the propulsion system, aircraft and airline operations can be designed to derive the benefits of condition monitoring equipment. Such equipment can provide an early indication of malfunction and, especially, pinpoint the specific component needing maintenance thus reducing secondary damage and eliminating shot-gun maintenance of control/accessory components.

- Improved Modularity - The entire propulsion system must be designed using modular concepts so that failures and resulting removal and repair can be restricted to small equipment packages with little or no disturbance to the rest of the

propulsion system thus avoiding additional maintenance/shop costs and the opportunity for maintenance errors.

The benefits of modularity include ease of line maintenance, lower line and shop maintenance repair times, and reduced spare parts requirements. These factors in turn reduce aircraft delay times necessitated by component replacement.

Accessory drives should be isolated and modularized so that the engine or reduction gearbox can be removed without removal of most accessories. Also, required maintenance to such modules as accessory drive gearboxes could be performed without removal of the engine or reduction gearbox. The objective must be minimal equipment removal and disturbance to perform a maintenance action.

- Improved Hardware Reliability and Durability - Improved hardware reliability must be achieved. Means to accomplish this include hardware simplification as measured by lower parts count, use of improved materials, and improvement upon historical problem areas such as leakage.
- Core Engine and LP Turbine - The core engine and the LP turbine of the advanced turboprop system will make use of those proven technologies that are available today or can reasonably be expected to mature prior to introduction into service. Core engine and LP turbine technology generally available to all versions of gas turbine engines can be incorporated into the advanced turboprop system.
- Anti-Icing and Improved Blade Heaters - The propulsion system should be critically evaluated to eliminate if at all possible propeller anti-ice features. If this is not possible then blade heaters must be improved. The current 54H60 blade heater is a rubber covered wire heating element which is susceptible to environmental damage (FOD and erosion) and subsequent heater element failure. An improved heater concept, less susceptible to these problems, must be developed to lower the frequency of heater failures. This in conjunction with improved modularity, allowing individual blade replacements, will have a significant impact on cost related to heaters.

Based upon a relatively in-depth preliminary design study of an advanced turboprop propulsion system that incorporated the above features, a mature system maintenance cost was calculated. For the same duty cycle, the maintenance cost per flight hour of the advanced system was reduced to approximately 40 percent that of the current system at its maturity. This was largely due to the

elimination of scheduled overhauls. In projecting the maintenance cost of an advanced turboprop that incorporated the recommended reliability and maintenance characteristics, the maintenance cost of the advanced propeller (Prop-Fan) and gearbox was estimated at \$0.73 versus \$2.40/EFH for the fan and reverser of an advanced turbofan. The core costs of the advanced turboprop and advanced turbofan were comparable. The estimated maintenance costs of both the advanced turboprop and advanced turbofan were less than the JT8D. The reductions were largely due to the elimination of scheduled overhauls. The conclusion was that an advanced turboprop and an advanced turbofan, using similar cores, will have very competitive maintenance costs per flight hour. Maintenance cost does not appear to be a valid barrier against possible airline use of future turboprops.

5.2 Recommendations for Future Technology Development

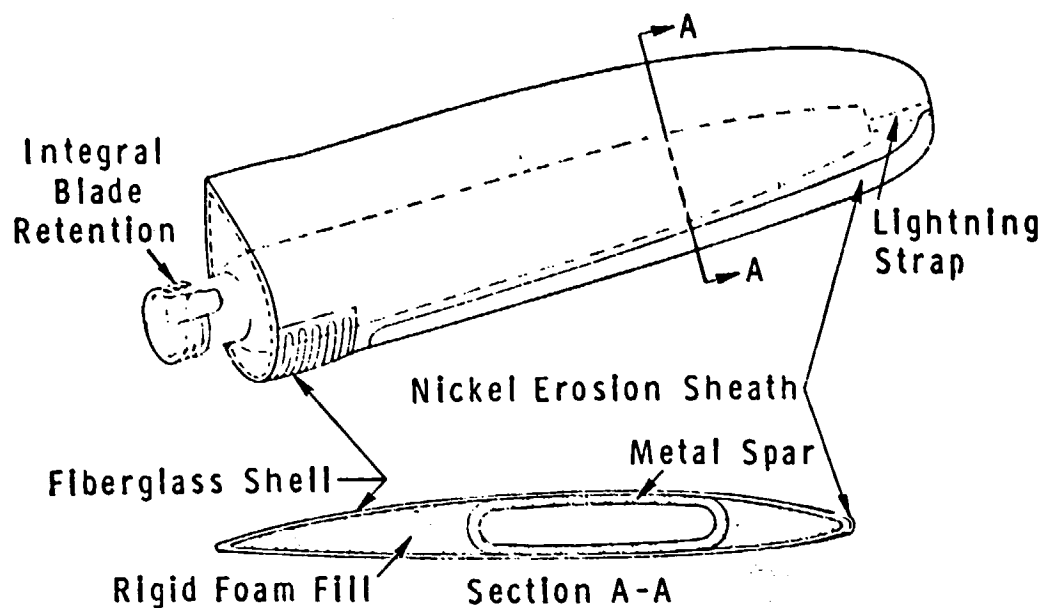
5.2.1 Prop-Fan Blade

The Prop-Fan blade is one of the most important components in the advanced turboprop propulsion system insofar as technology is concerned. The blade is critical with regard to meeting performance, noise, weight, and safety goals. It also is the largest contributor to both maintenance and acquisition costs, and it is the longest lead time component.

The Prop-Fan blade concept is fundamentally the same as the steel spar/fiberglass shell propeller blades which HS has had in service for over a decade. Both a Prop-Fan and a typical HS production blade are shown in Figure 5.2.1-1. Both exhibit a one piece structural metal spar with integral retention, a lightly loaded shell which forms the airfoil, a cavity filler, and leading edge protection. The Prop-Fan blade, however, is different in that it has thinner airfoil sections and a swept blade planform shape. These differences combined with its intended operation at 0.8M may require the use of different materials in the shell, filler, and possibly leading edge sheath. The blade ice protection system features a new heater concept for improved durability. Additionally, fabrication processes, both for the new materials and the unique swept spar, will require demonstration of advanced blade manufacturing processes.

While the Prop-Fan blade springs from a strong technology base, there are enough differences to warrant a technology program. This program should include both traditional spar/shell blade development tasks and some unique efforts aimed to address the new features of this blade. A recommended program should have three areas of effort.

CURRENT PRODUCTION FIBERGLASS PROPELLER BLADE



TYPICAL PROP-FAN BLADE

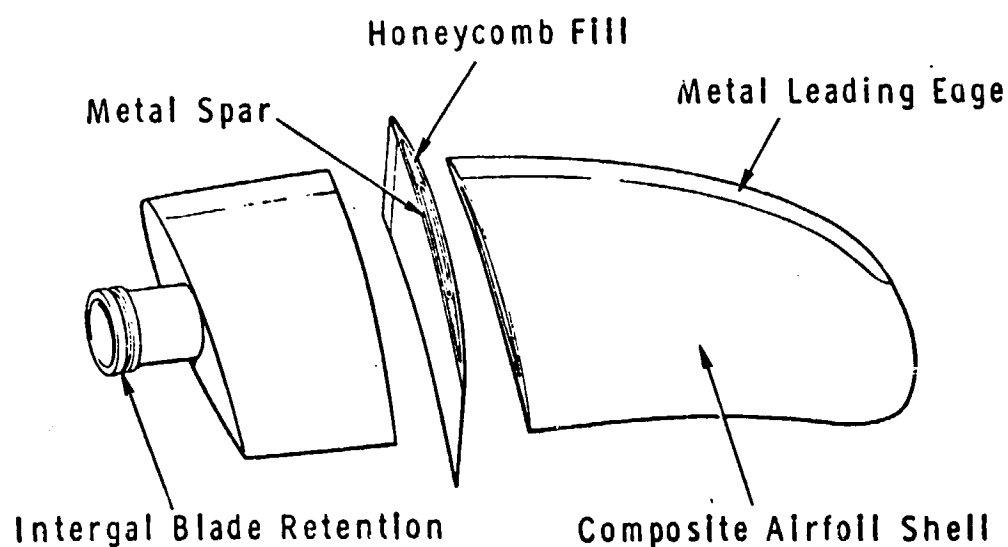


Figure 5.2.1-1 Comparison of HS Prop-Fan blade with HS current design.

The first area of the program should include screening evaluations of proposed shell materials systems for strength characteristics. Fill materials and adhesive system should be similarly evaluated. Spar efforts should initially involve tests to insure that a hollow, thin swept configuration can be fabricated with satisfactory material qualities. Following the screening evaluations, selected materials systems should be further evaluated using leading edge specimens. The specimens should be impact tested to measure FOD capabilities. These tests should isolate the most promising of the candidate materials. Outboard sections of the blade should be fabricated from these materials and whirl impact tested with simulated birds, ice balls and stones, water, sand and dust. Additionally, one piece metal sheet heaters of various materials should be fabricated. The heaters should be attached to simulated sections of the blade and instrumented to determine the temperature distribution both on the heater and inside the blade shell. The samples should be tested to determine their operation both before and after exposure to foreign object impact and to erosion.

The second area should be directed at acquiring early operational flight experience on Prop-Fan type blades. By using an aircraft such as the Lockheed P3, it is possible to have advanced blades operating in a service environment long before an all new advanced turboprop propulsion system would be ready to install on an operational aircraft. Although the aerodynamic design of such a blade for such a service test aircraft would differ from that required for an 0.8M airplane, the service test blade would be designed with the same thickness, operating stresses and could be manufactured with the same processes and materials as the 0.8M design. A program of this nature should provide basic structural and dynamic data, environmental experience with regard to blade surface damage tolerance, data regarding performance and acoustic payoffs due to thickness ratio reduction and sweep at subsonic blade tip helical M, and blade field repairability data. The program would consist of limited laboratory tests on the full scale blades, a flight release program on a T56 engine, incorporating new blades in existing propeller assemblies, and operation on P3 aircraft.

The third area should address the full scale Prop-Fan blade. This effort should take the material screening and spar forming work, specimen and blade section tests, heater work, and the blade work associated with the P3 tests, and bring them together into a final blade concept for manufacture and testing. This full scale blade program should include tests on single blades, such as experimental

stress analysis, bending and torsional fatigue, foreign object impact, and lightning strike, and system tests with a full rotor on an engine to evaluate operating stress and vibration, stability and response.

5.2.2 Main Drive Reduction Gearbox

The reduction gear design projected herein is not a completely engineered design. A number of studies are still required to verify some of the design choices noted in the previous sections. The predicted low premature removal rate of the gearbox together with its relatively low acquisition cost (less than the current T56/501 gearbox) resulted in an exceptionally low maintenance cost per flight hour for the gearbox. This result is a large factor in making the advanced turboprop system more competitive with the turbofan in maintenance cost. Further design studies such as the following are recommended:

- Analysis of integral vs. non-integral inner race and flanged vs. non-flanged outer race bearing designs based on life-weight-cost considerations. This can best be accomplished by utilizing the DDA DOC computer program and/or value engineering department analysis.
- Design and analysis of mechanisms for insuring equal load sharing between the two idler gears. One possible scheme is the use of tapered roller bearings and mismatched helix angles for the two gears on each idler. The slight thrust load difference thus produced would be balanced by a hydraulic piston located co-axial with each idler in contact with the bearing outer race. A valve attached to the piston would control the pressure oil supply into the piston to increase piston pressure as needed to balance the thrust load. Interconnecting the pistons for the two idlers would cause one idler to slightly shift axial positioning to balance the thrust loads on the two idlers.
- Analysis of gear and bearing loads to select optimum first/second stage reduction ratio split and axial location (first stage toward front or toward rear of gearbox) and propeller shaft bearing spacing. Helix angle optimization and center distance should also be included. This study can be best accomplished by writing a computer program based on the general gear arrangement to calculate the operating loads, select bearings, and calculate weights; then vary the ratios, helix angles, bearing spacing, etc., until an optimum is determined.

- Analysis of gear tooth surface fatigue life based on Reference 6 should be made and reported. DDA experience to date should be reviewed in depth to assure that current crushing stress design limits are adequate for the long life expected from this advanced propulsion system.
- Alternate methods of propeller mounting in addition to the one selected for inclusion in the concept design should be studied. One alternate is a shaft integral with the propeller disk which assembles through a gearbox shaft that supports the second stage reduction gear. The propeller shaft is located in the gearbox shaft on two stepped press fit pilots on each side of a drive spline. This alternate propeller mounting method is very similar to the method used to mount large fans on current engines. Final selection should await the recommended detail discussions with potential airlines especially regarding their recommended/planned maintenance concepts. Trade offs are assembly/disassembly time, retention of propeller modules in convenient assemblies, record keeping, and overhaul/repair costs of modules requiring propeller removal against a weight difference of approximately ten pounds.
- The dual compound idler study concept is slightly heavier and has a larger frontal area than a comparable planetary system. Trade-off studies should be conducted between the two systems to determine the effect of size and weight versus overall system size and DOC.

Following detailed design studies a development program should be conducted for either demonstrator or full scale flight test programs to prove the predicted capability of the final choice.

5.2.3 Advanced Turboprop Design Definition Study

The engine concept used in the maintenance study represented advanced technology for 1985 to 1990 IOC. The engine was configured for 25:1 pressure ratio and 2360°F BOT. Its configuration is a single spool with a free power turbine. While it represents one of the simplest approaches to an advanced turboprop engine other configurations should also be analyzed, including the effects on maintenance costs.

The objective of the design study should be to define the engine, reduction gearbox, and control system, which together with the Hamilton Standard Prop-Fan concept and the complete consideration

of the aspects of the propulsion system interaction and integration with the airplane wing or airframe, would provide a turbo-prop system whose installed specific fuel consumption would result in minimum achievable energy consumption in an 0.8M 1985-1990 IOC transport aircraft.

A range of parameters should be identified and analyzed for turbo-prop propulsion system concepts that offer reduced energy consumption for subsonic transports. These systems should include the engine, reduction gearbox, and the Hamilton Standard Prop-Fan as well as the nacelle shape, inlet, and nozzle. The engine study should include, but not be limited to the following configurations:

- Single spool - this configuration offers excellent thrust response times and has the simplest compressor/turbine rotor system but requires an extension of current single spool overall pressure ratio levels.
- Free power turbine, single spool core - this system is a direct adaptation of current free turbine turboprops and some fan engine general arrangements. Overall pressure ratio will require extension beyond current turbofan core levels of 16:1 on a single spool.
- Two spool - the two spool turbofan arrangement with the fan driven from the low pressure spool represents the most straightforward approach to achieving the desired levels of overall pressure ratio since contemporary turbofan engines have fan hub and low pressure compressors plus core compressors with overall pressure ratios of approximately 30:1. For prop-fan application, the equivalent of the fan hub compression would be produced with one or two additional low pressure system stages to maintain the overall pressure level. This system introduces compressor and control system complexities when off-design and transient characteristics are considered.
- Free power turbine, two spool core - this arrangement, used in a current high pressure ratio turbofan engine, offers a direct method of achieving the desired level of overall pressure ratio with existing compressor technology. However, some added mechanical complexity and compression system tailoring requirements are introduced.

The effects of variations in the major thermodynamic parameters should be computed for each configuration in order to determine optimum cycle combinations and to display trends in uninstalled and installed performance, and in geometry and weight. The over-

all propulsive efficiency of a turboprop system includes the thermal efficiency of the engine, the efficiency of the Prop-Fan, and the gearbox capability to match engine and propfan at their best operating speeds. Component technologies should be incorporated that are appropriate for engines entering service in the 1985-1990 time frame. Any prior work on relevant components or cycles that are available should be reviewed and utilized to the fullest practical extent. Results of work would be utilized that were directed toward increasing operating pressures, component efficiency, and turbine temperature, and reducing turbine cooling air requirements and gas path leakage. Turbine inlet temperatures up to 2800°F and overall pressure ratios up to 45:1 should be analyzed.

The following characteristics or parameters should be computed for each turboprop system considered:

- Thrust over the expected range of flight Mach number, altitude, and throttle settings.
- The corresponding thrust specific fuel consumption rate.
- Propulsion system weight, with and without nacelle, inlet and nozzle.

In computing the characteristics or parameters for each turboprop system the following analyses should also be included:

Operational Analysis: In order to optimize the steady-state and dynamic operating characteristics of the combined engine and Prop-Fan detailed studies should be made of the performance, dynamics, and required safety features of the complete system.

Installation Analysis: Installation analyses should be conducted in support of the aircraft studies that would include the following considerations:

- Inlet and exhaust arrangement and location.
- Nacelle drag.
- Gas turbine inlet distortion, pressure recovery, and losses.
- Component/module accessibility.
- Engine, gearbox, and propfan integration.
- Airframe integration

● Mount arrangement.

Mechanical design activity is needed to verify that design and system performance goals are fully attainable. The entire propulsion system must have uncompromised safety, long life, high durability, and competitive life cycle costs. In addition, the system must meet performance, noise, and weight goals. While the propulsion system concept would be fairly well established, many details of the propulsion system would have received only limited attention. It is the intent of a mechanical design program to bring a large measure of finalization to a propulsion system which meets the design objectives established for it.

The starting point for a mechanical design program would be the work represented by the propulsion system concept in this maintenance study report. A preliminary design requirement document Appendix A has been prepared as well. The elements of a mechanical design program would be configuration design studies, preliminary system design, and system design.

Configuration design studies should be conducted on the major Prop-Fan and engine modules and on the system installation. This task should begin with a system concept (per this report) and a preliminary design specification. Design studies should be performed to assess various design concepts against the specification requirements. Preliminary selection of propulsion sub-system interfaces should be made. Concepts should be chosen based on these studies and on discussions with the pertinent Federal regulatory agencies such as FAA, aerospace manufacturers, and potential user organizations such as airlines and the military services. Finally, the design specification and system concept should be updated to form the basis for the next program element, the preliminary design task.

The preliminary design activity would bring into focus the Prop-Fan and engine system characteristics before the final hardware design is initiated. The intent of this effort should be to provide confirmation of mechanical design concepts and compliance with design objectives. Based on the results from the preliminary system design, a detailed final design should be performed. This design work should provide a firm basis for finalizing advanced turboprop data and characteristics such as performance, weights, maintenance features, reliability, costs, etc.

6.0 AIRLINE REVIEWS AND COMMENTS

Upon completion of the draft of the technical portion of this report, it was submitted to United Airlines and Frontier Airlines for their review and comment. The draft submittal and review was followed by meetings and discussions covering any questions that may have been unclear in the written draft.

Following is a summary of the replies from both airlines.

6.1 United Airlines

United Airlines had no serious reservations as to the projected maintenance costs for the propeller-reduction gear section and generally agreed that the turboprop core maintenance cost should be no greater than that of a turbofan core for propulsion systems of equal thrust and technology. United concluded that credibility of the maintenance cost estimates in the report was enhanced by the planned high degree of maintainability and repairability of the propulsion system, and by the comparative simplicity of the reduction gearbox.

6.2 Frontier Airlines

Frontier Airlines is still operating the DDA 501-D13 engines and has accumulated over 1.7 million engine flight hours. Frontier concurred with the removal rates and maintenance costs of the 501-D13 engine and 606 and 54H60 propellers as stated in the report. Frontier questioned the maintenance cost of the JT8D fan as quoted in the report. Their experience indicated a lower cost, but admittedly did not include the disk cost. A further check with United Airlines and Pratt and Whitney corroborated the figures shown in Section 3.4.3, and indicated that the material costs of the disk were approximately 1/3 of the total fan maintenance cost.

Because of Frontier's experience with the 501-D13 engine, they expressed doubt over the achievement of the MTBR goals for the reduction gearbox (33,333 hrs) and the LP turbine (50,000 hrs) for the future turboprop system. With respect to the gearbox, following is a tabulation of data from . 3.5-16 of this report and the CY 1977 data tabulated in the Frontier report.

Comparative Reduction Gear Premature Removal Rates (PRR's) and MTBR's

CY 1965-68, 1975, and 1977

| | CY 1965-68 | CY 1975 | CY 1977 |
|-----------------------------------|------------|---------|---------|
| Premature removals per 1000 EFH's | 0.154 | 0.031 | 0.025 |
| MTBR's, hours | 6,494 | 32,258 | 40,000 |

Frontier reported that the large improvement shown in CY 1975 and 1977 is mostly due to the fact that the gearbox is repaired on-the-wing and a removal is not charged. DDA believes that similar rates can be achieved without the costly "on-the-wing" repairs through the proposed design incorporating increased reliability in the main drive gear system and provision of a remote drive for aircraft accessories. Frontier agrees that the latter would be a great improvement, as the accessory drives are a source of much of the on-the-wing repair costs. The proposed inherent MTBR of 33,333 hours is consistent with the 32,258 and 40,000 hours from the CY 1975 and CY 1977 records. An MTBR of 25,000 hours that included non-inherent removals was used in estimating projected maintenance costs for the advanced gearbox.

While Frontier did not quote specifics on the LP turbine, DDA checked removal records of the 3rd and 4th stages of the T56 turbine and the LP turbine of the TF41. This data did not indicate that the 50,000 hour MTBR was unrealistic for future designs.

From their experience, Frontier stated that the fuel control system was the weakest link in the engine components. They stated that the proposed control system was excellent, but that it needed to be built and tested, and that the MTBR should be on the order of 10,000 hours. This is probably based on their experience with turbofans since the current hydromechanical control on the JT-8D engine has a MTBR level of around 10,000 hours. In a recent proposal on JT-9D engines where the hydromechanical control system (also experiencing about a 10,000 hour MTBR) was to be replaced with a nacelle mounted electronic supervisory control and an engine mounted hydromechanical fuel control with electromechanical interfaces, the predicted MTBR's were 8400 hours for the new electronic control and 7,000 hours for the new hydromechanical control. The fuel control system would then have a 3800 hour MTBR. A reduction in reliability is a common situation in going the mechanical to electronic route but the lower reliability must be traded off against the benefits which result with the improved control systems being offered today.

Advantages with an electronic system include a reduction in In-Flight-Shutdown, Delay, and Cancellation Rates due to control system redundancies. Additionally, the electronic control system offers improvements in fuel economy, greater schedule flexibility and significantly reduced pilot work load. When all of these matters are considered, the electronic control system has significantly better Life Cycle Cost benefits over the hydromechanical system.

The full authority digital electronic control specified by DDA includes engine, propeller, and synchrophaser functions. It is fully redundant, fail operational, and operates in a 200°F temperature environment. The predicted MTBR is 2800 hours. Comparing this to the proposed electronic supervisory control mentioned above, we found it to have about 50% greater complexity and to be designed for a 90° higher temperature. These differences would account for a significant reduction from the 8400 hour MTBR. The temperature requirement alone reduces the MTBR in half. It is agreed that the proposed digital electronics control needs development, with incrementally higher goals than the currently predicted MTBR of 2800 hours.

Frontier believed that the projected PRR goal of .232/1000 hrs for major modules, primarily in the core engine, was conservative, compared to their experience with JT8D's. Turbofan and turboprop cores of equal technology should have about equal PRR's, and if improvements over the projection are realized, then the maintenance cost will be further reduced, providing the restored cost per repair does not increase disproportionately.

Frontier believed that the maintenance philosophy was excellent, and that the concept of fault isolation and condition monitoring was good but cautioned that the monitoring units must also be reliable to reduce the possibility of false indications. It is believed these conditions can be met in an advanced system.

Frontier stated that the advanced propeller design appeared feasible in function and should reduce maintenance requirements. Poor reliability has been their experience with blade de-icing heaters. The proposed metallic sheet type heaters should be the solution for reducing heater maintenance costs.

Frontier's understanding of the advanced turboprop lube system was that the propeller would be fed from the reduction gearbox. Since the reduction gearbox has been a metal generator, Frontier felt that a very fine micron filter would be necessary to filter the oil prior to entering the propeller. They pointed out that this would mean that excess metal generated in the gearbox would cause the filter to bypass resulting in contamination of the propeller. The intent of the proposed system is a common oil supply and cooler for the engine, reduction gear, and propeller, but separate systems will supply and scavenge each of them. In this way failure debris from each will be isolated for detection, and magnetic or high capacity filters will be necessary in the scavenge system after the chip detectors and screens. DDA believes that with a high degree of condition monitoring which include oil quality measurement devices that detect in an early stage many types of part failure, the proposed system could be feasible, resulting in failure isolation and minimization of replacement and repair.

Frontier summarized by reasserting their interest in advanced turboprop development providing that certain goals could be achieved such as:

- fuel burn consumption reduction of 15% to 25% lower than a comparable turbofan
- that sound levels in the cabin could be reduced to an acceptable level without adding significant weight to the aircraft resulting in lower payload and increased fuel burn.

This interest was stimulated by the following achievements:

- the NASA/advanced propeller model tests have attained close to 80 percent efficiency at 0.8M
- measured reductions in near-field propeller noise, and studies of fuselage attenuation, indicate cabin comfort (noise and vibration) can be made comparable to turbofans
- Studies by Boeing, Douglas, and Lockheed have shown that the new turboprop will reduce fuel consumption by 10 to 20% at 0.8 Mach number cruise compared to a comparable turbofan, or 20-40% relative to current turbofans; notwithstanding the extra fuselage treatment, higher propulsion system weight, and poorer wing performance due to the propeller slipstream assumed in these studies.

Because of the potential for the reduction in fuel consumption and costs, Frontier Airlines endorse the NASA Advanced Turboprop Technology Development Program and urge its continuation into flight demonstration of fullscale hardware. It is the opinion of Frontier Airlines that the following should receive top priority:

- fullscale flight hardware
- work toward reducing the goal total major module premature removal rate to .15/1000 hours, possibly through increasing the MTBR in the core engine
- build an advanced gearbox to determine feasibility of design and potential reliability
- build a fuel and control system to determine feasibility and potential reliability.

APPENDIX A

ADVANCED TURBOPROP PROPULSION SYSTEM DESIGN REQUIREMENTS

REFERENCES:

- A. Federal Airworthiness Regulations, Parts 25, 33, 35, and 36.
- B. An Airline Study of Advanced Technology Requirements for Advanced High Speed Commercial Transport Engines - Vol. III Propulsion System Requirements - NASA CR 121134

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| 5.0 | Installation Requirements |
| 6.0 | Propulsion System Control |

1.0 General

The design requirements set forth herein are applicable to an advanced turboprop propulsion system for commercial airline operation with an initial operational capability (IOC) in the 1985-1990 era. These requirements have been defined with the intent to be consistent with the basic criteria of safety, minimum cost of ownership, and suitability for commercial airline operations. Design tradeoffs shall be evaluated on the basis of minimum cost of ownership consistent with safety and airline suitability. Cost of ownership includes the total impact to the airlines of labor, material including fuel, and outside service costs.

The propulsion system includes the propeller, the main drive reduction gearbox, the power section, and installation parts, each of which consists of a series of sub-modules, as shown in Figure 1.0-1.

The power section accessory gearbox provides drive pads for only those accessories required for the basic propulsion system. However, a separate power takeoff pad is provided on the aft side of the main drive reduction gearbox which will accept a quill shaft to drive a separate aircraft accessory gearbox mounted in the aircraft.

A typical propulsion system installation is shown in Figure 1.0-2.

2.0 Operational Requirements

2.1 Propulsion System Ratings

The propulsion system ratings and flight operational limits shall be as shown in the Propulsion System Model Specification. Ratings shall be in terms of both thrust produced and horsepower.

2.2 Safety

The power section shall be designed to contain all parts damaged or released by the failure of any one compressor or turbine blade in the hub section.

The propeller blades will be capable of operating for 35000 flight hours without major maintenance. The blade spar will have an infinite life without catastrophic failure.

The pitch change module contains a pitch lock mechanism. In the event of failure of control pressure or input signal, the pitch lock mechanism will limit blade motion toward low pitch within two degrees of the blade angle at failure.

Under no circumstance shall the blade retention fail such that loss of a blade occurs.

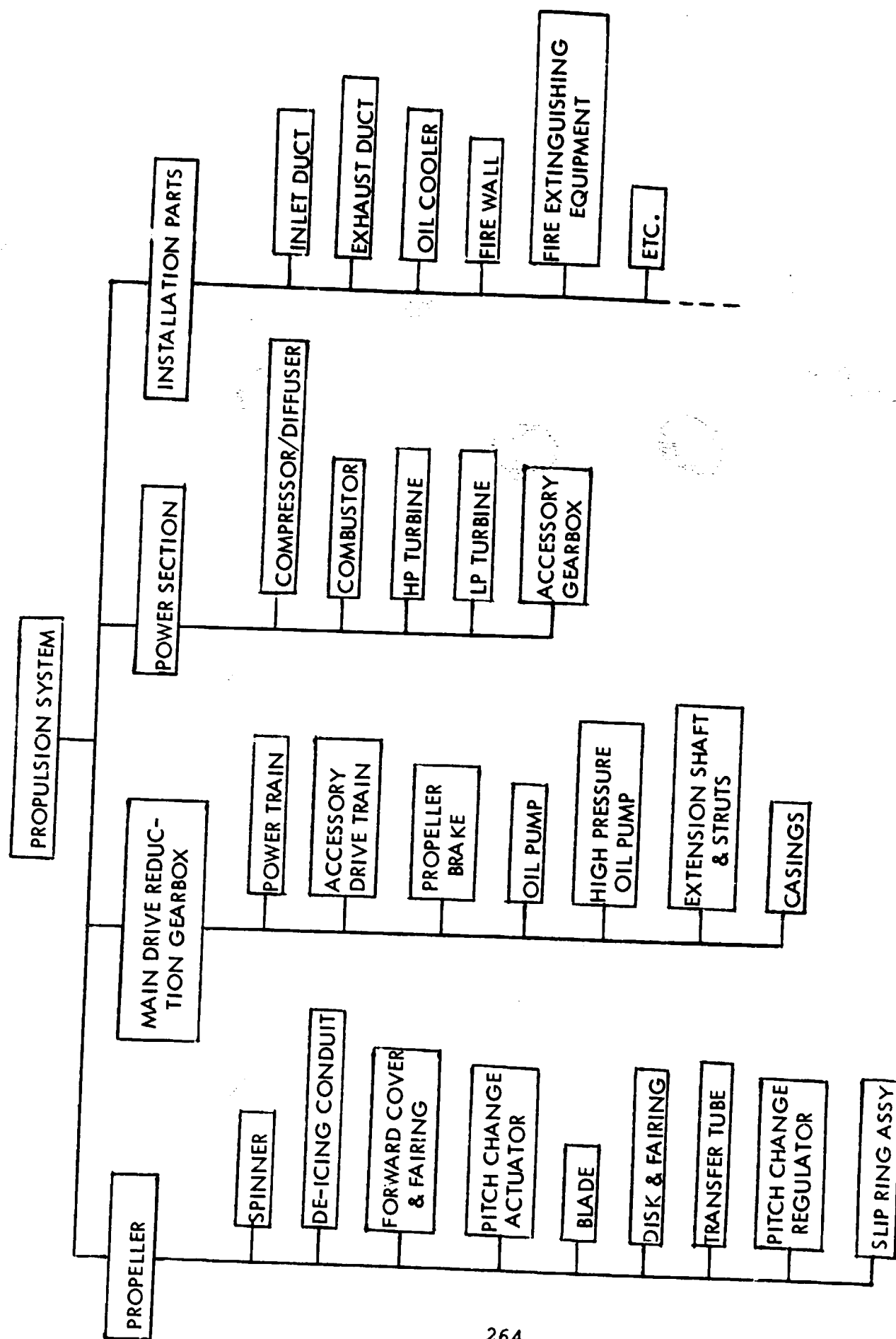


Figure 1.0-1. Propulsion System Modular Breakdown

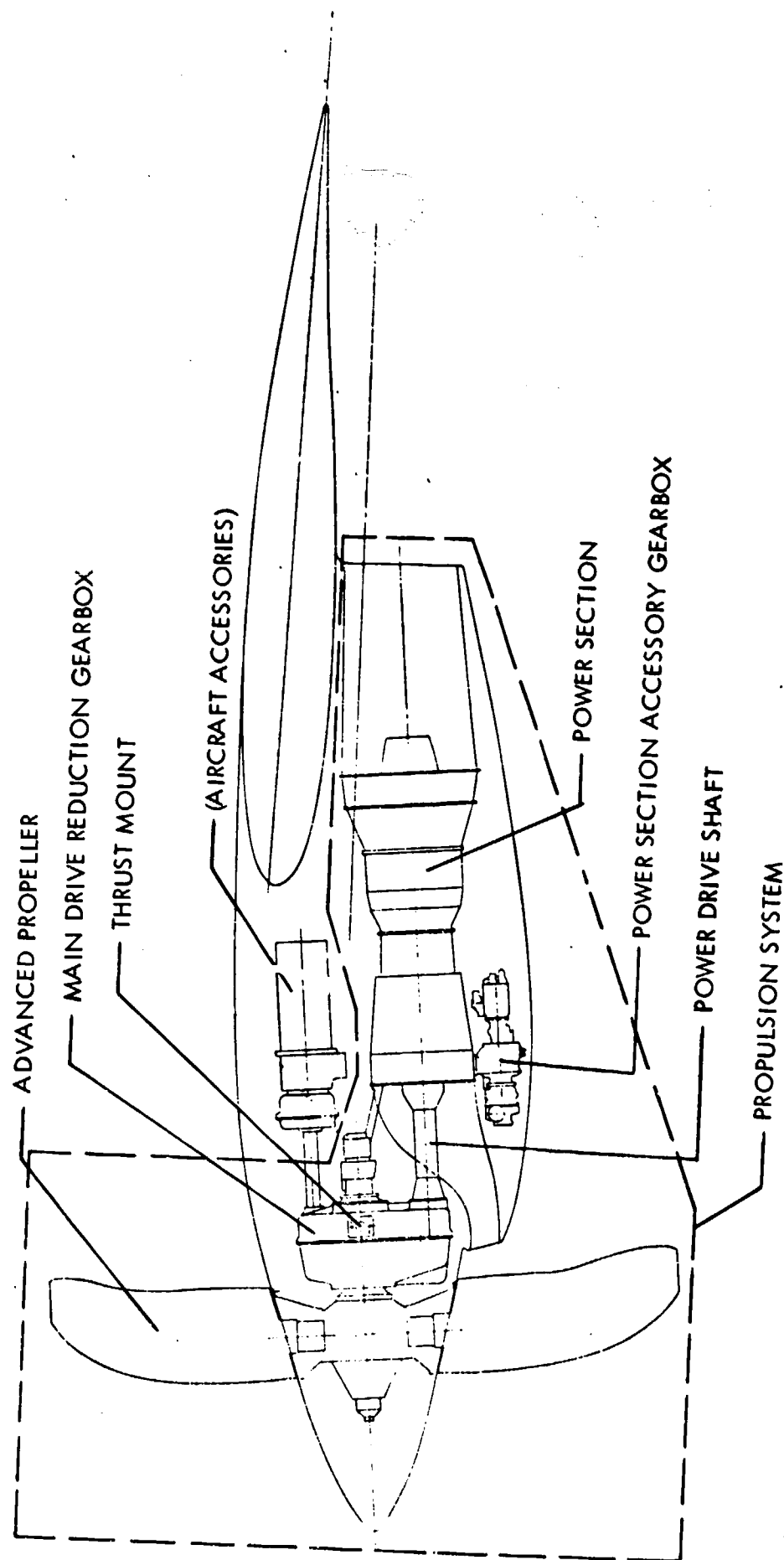


Figure 1.0-2. Propulsion System General Arrangement

2.3 Air Bleed

Air for aircraft services will normally be supplied by an aircraft furnished compressor on the aircraft accessory box. Should power section bleed air be required flow limiters shall be installed where required at or near each power section bleed port to minimize the flow of engine compressor bleed air in the event of the loss of manifold integrity.

2.4 Flight Maneuver Forces and Loads

The propulsion system and its support points shall withstand without permanent deformation, the general flight, gust and landing load limits given on Figure 2.4-1. The calculated weight of the propulsion system shall be increased by the specified weight allowed for all power section accessory gearbox mounted accessories and by the weight of all propulsion system components which are mounted on either the power section or the nacelle.

All the loads given in the following paragraphs of this section assume axial forward and reverse thrust.

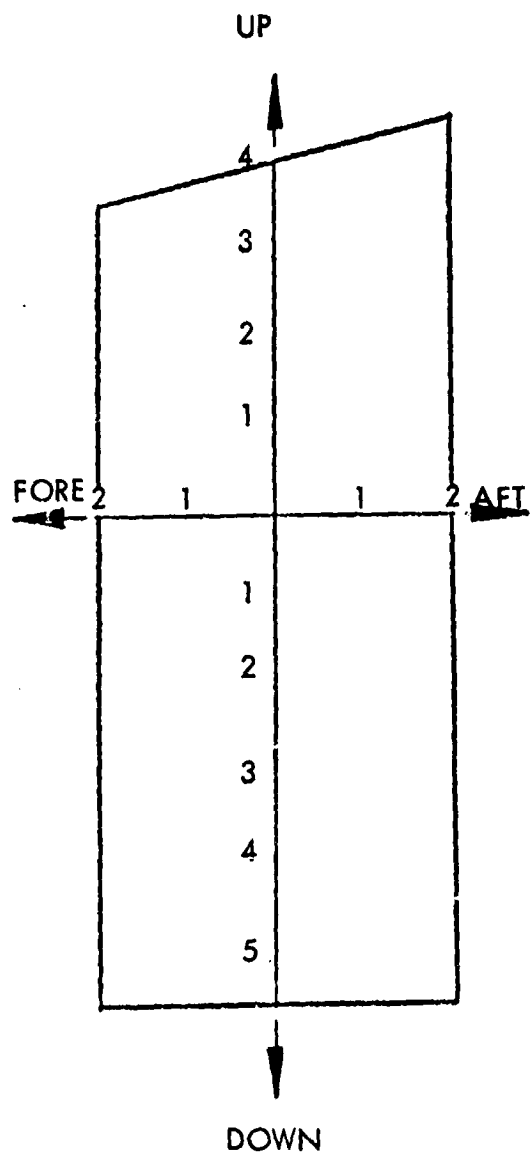
Load factors and angular velocities are taken at, and about, the center of gravity of the propulsion system and are relative to the propulsion system axes.

An ultimate factor of 1.5 is to be applied to each of the limit load cases and to the limit load cases given in a. below to obtain the corresponding ultimate load cases. The emergency landing loads given in b. are ultimate load cases only.

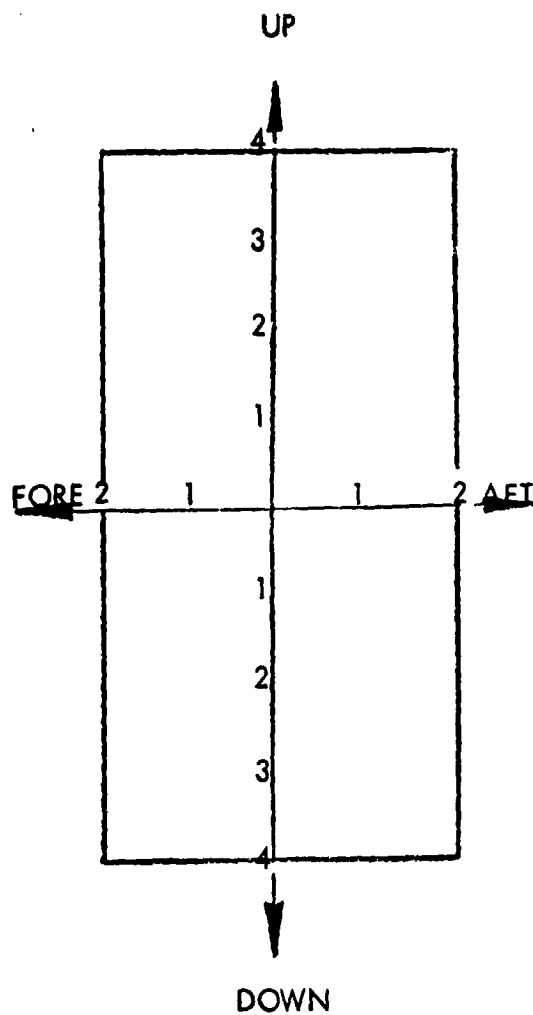
- a. Additional loads - The propulsion system mounts shall be designed to also withstand the following load limits:
 - 1. A side load factor of ± 1.33 but without other inertia factors with zero to maximum thrust.

0 TO MAX. FWD. THRUST
 SIDE LOAD = $\pm 1.0G$
 PITCH PRECESSION ± 0.5 RAD/SEC

MAX. REV. TO MAX. FWD. THRUST
 SIDE LOAD = $\pm 1.0G$



GENERAL FLIGHT AND GUST CASES
 (LIMIT LOAD)



GENERAL LANDING CASES
 (LIMIT LOAD)

Figure 2.4-1. Propulsion System
 Load Envelopes

2. A yaw velocity of 1.0 radian per second with maximum reverse to maximum forward thrust, together with a load factor of 1.0 down, ± 1.0 side and ± 1.0 fore and aft.
 3. A seizure of any shaft system in 1.0 second together with a load factor of 1.0 down.
- b. Emergency landing loads - The propulsion system shall be designed to withstand the following emergency landing loads.
1. A load factor of 12 forward, together with a downward load factor of 6.
 2. A load factor of 11.6 forward together with a side load factor of ± 3.1 .
- c. Slings - The slinging points shall be designed to withstand an ultimate vertical load of ± 4 .

2.5 Propulsion System Mounting

Mounting provisions shall be provided on the propulsion system which are capable of absorbing the maneuver forces and loads described in paragraph 2.4, while providing for thermal expansion. The mount pads shall be suitable for the installation of vibration isolators capable of adequately isolating vibration at propulsion system rotational speeds.

The propulsion system shall also be provided with slinging points which shall be located on the power section diffuser/combustor module to permit hoisting and/or storing of the propulsion system such that the other major modules of the propulsion system may be removed without disturbing the slinging point attachments.

2.6 Vibration

The propulsion system shall be free of destructive vibration at all operating speeds. The maximum vibration limits and points of measurement shall be shown on the installation drawing.

2.7 Anti-Icing

The propulsion system with all anti-icing protection systems operating shall meet the requirements specified by applicable Federal Aviation Administration Regulations. An

automatic anti-icing system shall be provided. Continuous operation of the anti-icing system shall not damage the engine. If failure of the anti-icing occurs, it shall remain in or revert to the anti-icing mode. The anti-icing system shall utilize bleed air from the power section compressor. A design objective shall be to eliminate the need for propeller anti-icing. Should propeller anti-icing be required, an electric blade heater is proposed.

2.8 Noise

The following is the expected noise level requirement related to Appendix C of FAR 36 and the introductory year of aircraft operation.

Year

1980 to 1990

FAR 36 minus 10 EPNd B

Consideration will be given to the noise level produced by reverse thrust operation on the ground which must not exceed the sideline levels covered by the requirements stated above.

2.9 Pollution Control

The Federal Regulations for "Control of Air Pollution From Aircraft and Aircraft Engines" are currently being revised. In this revision process the EPA has assessed the technology required to control emissions from both current and advanced technology turboprops. Their conclusions are that the current technology will allow present power sections to pass the present regulations but future large turboprops are to be given emissions standards which are attainable only by using advanced methods of emission control. These methods are:

Fuel Staging
Variable Geometry
Premix, Prewrap fuel injection

To illustrate the level of technology and the amount of reduction which the EPA projects as achievable, their projected emission levels for an advanced technology/ 13,000 HP turboprop are compared with current regulations for turboprops below.

| <u>Pollutant</u> | <u>Present Turboprop Regulation * (Effective Jan 1979)</u> | <u>Level Advanced 13,000 HP Turboprop *</u> | <u>% Reduct.</u> |
|------------------|--|---|----------------------|
| HC | 4.9 | 1.4 | 71 |
| CO | 26.8 | 4.2 | 84 |
| NO _x | 12.9 | 9.5 | 26. |

* lb. pollutant/1000 HP-HR

3.0 Life and Reliability

3.1 Design Life

Design life is defined as the time or life that the propulsion system shall operate satisfactorily with scheduled maintenance, without scheduled part or component replacement, and with unscheduled replacement frequencies no more frequent than are consistent with the Mean Time Between Failure (MTBF) values. The following items shall be designed to be capable of operating for the following design lives.

- | | | |
|----|------------------------------|-------------|
| a. | Propeller | 35,000 hrs. |
| b. | Main Drive Reduction Gearbox | 35,000 hrs. |
| c. | Control System | 35,000 hrs. |
| d. | Turbine Airfoils | 20,000 hrs. |
| e. | All Other Parts | 35,000 hrs. |

3.2 Duty Cycle

The propulsion system design life is based on the duty cycle shown in Figure 3.2-1.

3.3 Mean Time Between Removal

Mean Time Between Unscheduled Removal (MTBR) based on propulsion system inherent events shall be no less than those shown in Table 3.3-1 for major modules and in Table 3.3-11 for components.

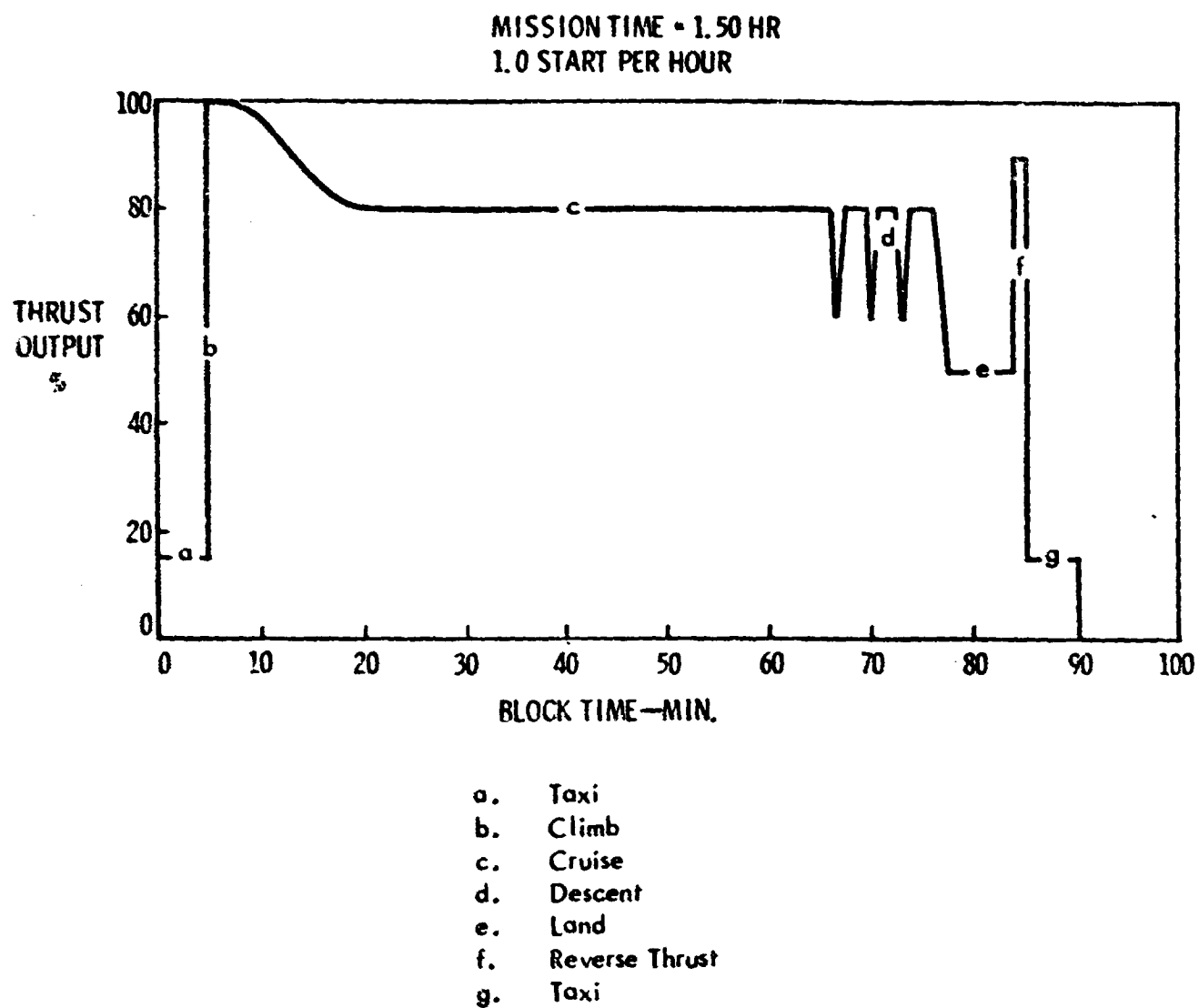


Figure 3.2-1. Advanced turboprop duty cycle.

Table 3.3-1. Inherent Reliability Goals for Advanced
Turboprop System - Major Module Removals

| MAJOR MODULES | INHERENT MTBR, HRS | CORRESPONDING REM RATE/1000 HRS |
|---|-----------------------|------------------------------------|
| Core engine | 6,250 | 0.160 |
| LP (power) Turbine | 50,000 | 0.020 |
| Power section accessory drive gearbox | 50,000 | 0.020 |
| Main drive reduction gearbox | 33,333 | 0.030 |
| Propeller disk | 500,000 | 0.002 |
| <hr/> Total for Major Modules (Inherent) | <hr/> 4310 | <hr/> 0.232 |

Table 3.3-II. Inherent Reliability Goals for Advanced Turboprop
System - Component and Accessory Removals

| COMPONENT OR ACCESSORY | INHERENT MTBR, HRS | CORRESPONDING REMOVAL RATE/1000 HR |
|--|-----------------------|---------------------------------------|
| Power section major accessories (Oil pump, scavenge pumps, fuel pump, ignition) | 50,000 | 0.020 |
| Power section minor accessories | 6,667 | 0.150 |
| Control system | 2,500 | 0.400 |
| Spinner | 200,000 | 0.005 |
| Pitch change actuator | 50,000 | 0.020 |
| Propeller blades (set of eight) | 50,000 | 0.020 |
| Slip ring assembly | 100,000 | 0.010 |
| Pitch change regulator | 20,000 | 0.050 |
| Variable delivery pump | 10,000 | 0.100 |
| Minor propeller components | 100,000 | 0.010 |
| Starting system | 3,700 | 0.270 |
| Total for components (Inherent) | 950 | 1.055 |

3.4 FOD and Erosion Resistance

The propulsion system shall be designed for resistance to foreign object damage and compressor erosion. The design features to meet this criteria shall consider the use of appropriate materials, and propeller blade tip to ground clearance. The power section design shall consider the location of the compressor inlet, compressor blade tip speeds and airfoil shapes, number of airfoils per stage, airfoil aspect ratio and chord, and axial spacing between vanes and blades.

4.0 Maintainability

4.1 General Maintainability Requirements

The propulsion system manager shall have total propulsion system responsibility in order to assure maximum maintainability characteristics.

a. Mounting

Each propulsion system package shall be attached to the airframe by fittings at the forward and aft support locations. The support fittings shall be designed to allow for thermal expansion of the propulsion system and shall permit removal and installation with standard tools. The airframe structure will incorporate provisions for the attachment and use of hoisting equipment for installation and removal of the propulsion system as required.

b. Removal

The propulsion system interface relative to the airframe shall be defined so that it will be possible to remove and install the propulsion system with the minimum number of disconnections. These disconnection points shall be controlled to maintain full interchangeability.

c. Ground Support Attachments

Attachment points shall be provided on the propulsion system for support of the propulsion system on ground equipment independent of the airframe mounts.

d. Adjustments and Inspection

- Access to propulsion system adjustment and inspection points (including borescope holes) shall be provided where possible without the necessity of removal of any components other than cowlings, fairings, and propeller spinner. Where this requirement cannot be met, means for ready removal of the adjacent components shall be provided.
- The design must permit and provide for borescope inspection to the maximum extent possible. Borescope provisions for rotating components should all be located on the same side of the engine below the horizontal centerline and must be free of obstruction for rapid access as installed.
- Provide for borescope inspection of combustion section. Locate a sufficient number of borescope ports to facilitate inspection of fuel nozzles, combustion liners, and first stage turbine vanes and blades.

- Provide means to manually rotate engine rotors for borescope inspection.
- A maximum capability shall be provided to perform all propulsion system maintenance while aircraft installed.

e. Wrench Clearance

Clearance for use of wrenches and other similar maintenance tools shall be provided.

f. Maintainability Features

Maintainability features must be incorporated in the early concept stages of a new propulsion system design. Categories for consideration are:

- Inspection capability
- Line replaceable unit access
- Line replaceable unit repair
- Line unit replacement
- Serviceability
- Minimization of maintenance error potential
- Logistics

4.2 General Propulsion System Design Guidelines

a. Installation Error

Wheresoever possible, part design should make improper assembly a virtual impossibility. Reliance upon drawings or decals to convey assembly instructions is sometimes unsatisfactory because of the unavailability of proper drawings and/or personnel negligence.

b. Part Identification

Wheresoever possible, the manufacturer's part number should be permanently inscribed on a part. Packaging identification or the attachment of an identification tag should never be specified unless permanent marking is precluded by part size, or where an unacceptable stress concentration would be encountered.

c. Vibration Recording

Vibration pickup points should be provided at various locations to facilitate future service life evaluation and diagnosis. Such pickup points should be designed to be free from resonance to minimize the possibility of false data.

d. Special Tools

Design equipment so that it is maintainable to the following order of priority:

- Without tools
- With common hand tools
- With customer standard tools
- With special tools

e. Overtorquing

For locations where overtorquing a fastener would result in damage to parts, it is desirable to make provision to prevent this occurrence. This may be accomplished by specifying the torque and providing sufficient clearance for a torque wrench or utilizing torque limiting nuts.

f. External Tubing

~~External tubing on the propulsion system will be subject to chafing from contact~~ with adjacent parts unless it is properly anchored and clamped. To minimize wear and maintenance, it is desirable to clearly mark the tubing and/or illustrate the clamp locations with adequate drawings. Tubing should be routed so that removal of individual tubes does not require removal of other tubes or parts.

g. Propulsion System Modules

Modular construction shall be used for the propeller, main drive reduction gearbox, and power section, as shown in Figure 1.0-1. Propulsion system modules should be designed for individual replacement with the propulsion system installed in the aircraft. Support points must be provided in the nacelle and on the power section module for lowering, supporting and hoisting the propulsion system, independent of the main mounting pads, to accomplish module replacements.

h. Mounting Points

Propulsion system mounting points should be conveniently accessible. Attachment points, which are independent of aircraft mounts, should be provided for handling the propulsion system and/or modules in and out of the aircraft, the maintenance stand and the shipping container. Removal of splitline bolts to obtain lift attachments should be avoided.

i. Power Section Cleaning

The power section shall incorporate provisions for injection of a corrosion inhibiting fluid into the compressor for the purpose of cleaning. A simple connection shall be provided. When cleaning material is injected into the power section inlet to restore power, it is desirable to have the pressure sensing taps, bleed valves, oil lines, anti-ice valves, etc. arranged so that it is not necessary to disconnect and/or plug them to prevent contamination.

j. Fabricated Parts

Welded assemblies (bearing supports, vane segments, ducting, etc.) should be designed to be free from hidden welds which are inaccessible for inspection or repair. Areas which are subject to secondary damage and/or distortion should be designed as separable sections. Oil and air tubes should also be separable from welded structures.

k. Magnetic Plugs

Magnetic chip indicators should be provided at each main rotor bearing sump and also at each module where bearings and gears are used. This instrumentation provides a quick method to locate impending trouble which could save a major repair.

l. Bearing Removal

Provision should be made for bearing removal without bearing damage. This may require jack screws or slots on an adjacent flange. In case a puller is used, adequate clearance should be provided.

m. Thread Locking Devices

Prevailing torque, all metal self-locking nuts; lock plates; cup washers and automatically actuated locking devices are recommended for use with all threaded assembly devices. Lockwire and conventional tab washers should be avoided.

n. Interference Fits

High interference fits which require heating and/or chilling of components shall be avoided in assemblies which are to be subject to line maintenance.

o. Standard Parts

The number of standard parts used in a specific propulsion system should be reduced to a practical minimum, to minimize the overhaul parts inventory, the number of tools required, etc. This could be accomplished by standardizing such things as diameter, length, and head style of bolts, type of nuts, material and size of o-rings, etc.

4.3 Turbine and Compressor Assemblies

a. Assembly Index

Rotor assembly parts should be index marked to tolerate wheel/shaft separation and rejoining if necessary to assemble into the power section.

b. Blade Replacement

Rotor wheels should have an even number of blades - to simplify blade replacement by use of moment equivalent blade pairs to retain bladed wheel balance.

c. Blade Accessibility

Blade retention features should be accessible from the inlet (1st stage) of the rotor assemblies for release of blades without rotor disassembly. It is also desirable to be able to replace all blades in the rotor assembly without the necessity to disassemble rotor wheels.

d. Blade Serrations

Blade fastener bases should be one size for each stage so they can be installed without fit selectivity.

e. Rotor Installation

Rotor assemblies should permit attachment of bearings, slingers, labyrinths, nuts, locks, and spacers before installing the assembly into the engine. In addition, rotor assemblies should be stockable balanced and require no partial disassembly for engine installation. A balanced rotor assembly should retain acceptable balance when joined to any independently balanced rotor assembly; i.e., two rotor assemblies joined by a coupling.

f. Integral Seals

Labyrinth seal rotating knives should not be integral with expensive wheel or shaft parts. It is desirable to design replacement detail members so that in case of excessive wear, it would not be necessary to scrap a high value part.

g. Rotor Balance

Final rotor or bladed wheel balancing should be accomplished by adding or adjusting weights, not by removing metal. Removing metal is usually satisfactory for initial manufacture of the unbladed wheel disks, but not for major repairs, where unbalance may grow progressively worse.

h. Blade Inspection

Provision for visual inspection of the 1st stage compressor and turbine exit blades is desirable. Visual obstruction created by struts and variable vanes, prevents inspection for foreign object damage. If these obstructions are encountered, provision should be made by access plates or borescope points. Pressure or temperature sensing or bleed valve openings would qualify as access ports. It is also desirable to make provision to borescope intermediate stages and the 1st stage turbine vanes.

i. Case Removal

Segmented compressor and turbine case designs are recommended to facilitate blade and vane inspection without the necessity to disassemble the power section. This requires that attention be given to the type of pilots specified at the case end flanges. Inspection may also be expedited by keeping a case segment free from extraneous plumbing, wiring, accessories and control linkage to minimize removal time.

j. Case Inside Diameters

Blade tip seals in compressor and turbine cases should be presized to provide interchangeability and eliminate machining the inside diameter on assembly.

k. Vane Installation

It is desirable to have variable vanes sized for individual replacement. Stationary vanes should also have the I.D. or blade shroud sized to simplify replacement, preferably by small segments of a few vanes, individually interchangeable. Designs that require a dummy build of vane sets in cases to evaluate bores or axial positioning should be avoided. Interstage vanes located between two wheels of a balanced rotor assembly should not require wheel separation to install.

l. Wheel Spacers

Interstage spacers have an overhaul advantage when made separate from the rotor wheels. Separate spacers provide the convenience of replacement and make possible repair of worn surfaces.

m. Axial Adjustment

When assembling modules to the engine, it is desirable to have the rotor system designed so that axial positioning is not required. In case axial adjustment is necessary, the setting procedure should be simple and convenient.

n. Seal Bores

Bearing supports should be replaceable without the need to machine labyrinth seal bores. Equipment for this type operation is usually not available at overhaul bases. The seal bores should be replaceable inserts, as a repair convenience.

o. Bearing Races

Bearing races should be flanged or keyed against rotation to eliminate or reduce cage wear. This construction will minimize cage replacement at overhaul.

p. Monolithic Wheels

In cases of integrally cast bladed wheels (Monolithic), it is desirable to design for individual stage replacement without the necessity for assembly balance and machining. Maintenance bases do not have the equipment for these operations.

q. Serial Numbers

Turbine wheel serial numbers should be positioned so that they may be read without disassembly of the turbine rotor.

4.4 Combustion Section

a. Liner Inspection

The outer walls of the combustion case should be provided with access ports for borescope inspection of the liner while the power section is installed in the aircraft. Sufficient ports should be provided so that the liner can be thoroughly inspected.

b. Liner Replacement

It is desirable to make provision for replacing the liner with minimum power section disassembly. An acceptable method would be the removal of the HP & LP turbine modules as an undisturbed unit to give access to the liner.

c. Fuel Nozzles

Fuel nozzles should be externally replaceable.

d. Thermocouples

Thermocouples should be capable of in-place checking and ground calibration, and should be replaceable individually or by sub-groups independently wired for convenient separation.

4.5 Accessory Drive and Accessories

a. Oil Tank

A sight gage should be provided to determine oil quantity visually.

b. Filters

It is desirable to incorporate pop-out indicators on oil and fuel filters to indicate excessive pressure drop at a glance. A two-element oil filter should be used to prevent damage to bearings from oil contamination. Separate filters should be included for the main drive reduction gearbox, power section, and propeller.

c. Filter Drains

Provision should be made to locate convenient drain ports in the fuel and oil filters to remove excess fluid before filter removal. This arrangement promotes a clean nacelle to minimize fire hazard, and provides a source of fuel and oil samples for analysis and incipient problem detection.

d. Accessory Gearbox Location

The accessory gearbox should be located so that it is not necessary to remove ducting to service accessories. This arrangement expedites maintenance in an aircraft installation. The accessory gearbox serial number should be marked in a location where it can be read without removing components from the gearbox.

e. **Accessory Gearbox Handling**

Handling pads independent of engine mounting points should be provided for positive attachment of suitable equipment. Handling attachment points should be sufficiently rugged and located so that a gearbox can be moved with the accessories in place.

f. **Oil Seal Replacement**

Accessory drive shaft oil seals should be externally replaceable. Adequate clearance should be provided so that the seals are not damaged by threads or sharp corners on assembly.

g. **Accessory Replacement**

Accessories should be mounted so that each unit can be replaced, preferably by one mechanic, without disturbing an adjacent unit. There should also be sufficient clearance for adjustment of the accessories. No lubrication of the splines should be required when accessories are replaced. Power section oil or other means of lubrication should be provided for the splines.

h. **Gear Shims**

Replacement of the accessory gearbox without drive gear shimming is required.

i. **Standardization**

Standard off-the-shelf parts shall be used to the maximum extent possible to facilitate supply logistics and to avoid requirements for special support equipment.

4.6 **Main Drive Reduction Gearbox**

a. A propeller brake will be designed as a separate module so that it can be removed and replaced without disassembly of the gearbox.

b. Lube pressure and scavenge pumps when required should be externally removable.

c. Design should permit propeller installation and removal without requirement for bearing replacement and exposure of G/B to contaminants.

4.7 Propeller

- a. Modularity - Easy removal of propeller assemblies or combinations of parts (modules) will be facilitated by proper design.
- b. Adjustments - On-aircraft adjustments shall be kept to a minimum. The propeller shall be designed so that necessary adjustments can be accomplished with simple rigging fixtures and standard tools.

- c. Inspections

Preflight: A visual inspection of the propeller assembly shall be performed prior to each flight for purposes of confirming hardware integrity and identifying oil leakage.

Daily: Examine blades and spinner for evidence of FOD. Check for oil leakage.

Periodic (approximately every 500 hours):

- 1. Check brushes for wear. Replace brushes and clean the brush block and slip ring assembly as required.
- 2. Conduct daily inspection requirements in greater detail to identify impending problems which may require maintenance actions.

- d. Balance

Blades will be individually balanced to a master and all other rotating components will be individually mass balanced to allow component and blade pair replacement without rebalancing the propeller assembly.

- e. Diagnostics

Diagnostics to be provided for on-aircraft propeller fault detection and isolation shall include:

- 1. Vibration pickup to detect unbalance
- 2. Blade angle indication
- 3. Spectrographic oil analysis to detect contamination
- 4. Pitch change pump pressure and flow

4.8 Propulsion System Condition Monitoring

Propulsion system condition monitoring provisions shall be incorporated in new designs to permit detection of impending malfunctions and to define the required maintenance action. Early detection and correction of potential problems results in improved aircraft safety and reliability. Transducers which are required to measure component pressures, temperatures and positions, along with the associated wiring, must be integral parts of the basic design. For example, a fuel control with integral output instrumentation is preferable to the later addition of bolt-on monitoring equipment.

5.0 Installation Requirements

5.1 Drive Pads

The power section accessory gearbox shall provide drive pads for the following accessories:

- a. Starter
- b. Fuel pump/fuel control
- c. Oil pump
- d. Magneto power supply
- e. Centrifugal breather

The main drive reduction gearbox shall provide drive pads for the following additional accessories:

- a. Oil pump (LP - driven)
- b. Power takeoff (aircraft accessory gearbox drive)
- c. Hydraulic pump/propeller brake

The hydraulic pump will be used to boost oil pressure from the power section oil pump to 3,000 psi for the propeller actuation system.

All other aircraft-required accessories shall be driven by the nacelle-mounted aircraft accessory gearbox, which is not a part of the propulsion system package.

5.2 Lubrication System

The lubricant for the power section, the main drive reduction gearbox, and propeller, will be MIL-L-23699 or equivalent, and will be subject to an environment of -65° to 250°F. Standard oil lubrication shall be used in the propeller ball race retention, subject to the same environment.

5.3 Power Section Component Limiting Temperatures

Components mounted on the power section shall not exceed their allowable temperatures when surrounded by still air under the following conditions:

- a. Continuous operation with ambient air at the maximum stagnation temperature.

- b. In-Flight shutdown from the most adverse condition, and continued soaking with ambient air at the maximum stagnation temperature.
- c. Ground shutdown with ambient air at the maximum hot day conditions.

5.4 Fire Protection

Provisions shall be made between the power section and nacelle for convenient attachment of fireproof shields. In establishing the location, consideration of auto ignition of combustible fluids sprayed against the hot power section casings shall be considered.

All exterior lines and components which convey flammable fluid shall be fire resistant (15 minutes at 2,000°F (1,093.3°C)). Lubricating oil system components shall be fireproof (15 minutes at 2,000°F (1,093.3°C)). The lines should be routed and damped to provide separation from adjacent lines, components and external casings.

6.0 Propulsion Control System

The propulsion control system shall provide all control functions for total control of propulsion system performance through all required operational conditions. The integrated propulsion control system shall be designed for high reliability to require less maintenance than prior systems, consistent with the requirements of lower cost of ownership and high dispatch reliability.

6.1 Design Requirements

The control and fuel system shall be configured to utilize an advanced technology digital electronic controller for all required logic and computational requirements for the power section and propeller operation to accomplish the following control functions:

- a. Automatic built-in control/propeller system self-test for pre-start and operating monitoring.
- b. Automatic start sequencing.
- c. Power turbine inlet gas stream temperature limiting during all operation, including start, for turbine protection.
- d. H.P. turbine blade temperature limiting for extended turbine life.
- e. Control acceleration and deceleration fuel flow, bleed and compressor geometry for smooth and rapid operation without surge or flame out.
- f. Control gas generator speed as a function of power lever input position to provide modulation of engine power from max rating to idle to max reverse.
- g. Control propeller/power turbine speed over the required operational range.
- h. Limit maximum power turbine overspeed by an independent backup control function.
- i. System for autofeather based upon torque comparison within the electronic control and electronic control command to the propeller regulator.
- j. Provisions for torque limiting for gearbox protection.
- k. Provisions for automatic mode selections for optimum thrust control (takeoff, maximum climb, maximum cruise as a minimum).
- l. Provisions for digital link interfacing with flight control system for automatic propulsion control throughout all regimes of engine operation.
- m. Propeller synchrophasing.

6.2 Hydromechanical Components Requirements

The fuel handling components of the system shall be conservatively designed for high reliability and ease of maintenance. A single integrated hydromechanical assembly will include the functions of fuel pumping, metering, shutoff and supply for compressor geometry actuation. Suitable filtration will be provided upstream of the pump to minimize the effects of contaminants on all the hydromechanical components. The system shall be capable of operation under specified conditions of vapor/liquid at the fuel inlet. The pump shall utilize proven technologies for long life, high reliability operation on commercial fuels including: JP4, JP5, jet kerosene (ASTM 1655-65T) hydrafine processed fuel, and higher thermal stability limit fuels.

The unit shall include a suitable high reliability electrical interface with the electronic controller for metering valve actuation. Provisions shall be made for suitable means of detecting malfunctions of the interface device and of the system pressure compatible with the system check by the electronic controller. The system shall incorporate adequate redundancy features to provide backup operation of the fuel metering and compressor geometry functions in the event of failure of the primary electronic control. Reversion to backup operation shall be pilot initiated. In the backup mode the system shall provide for modulation of thrust over the range of Idle +5% to 90% maximum.

6.3 Digital Electronic Controller Requirements

An advanced technology digital electronic controller shall provide all control computations, scheduling, logic, interlocking and sequencing of all engine and prop-fan functions. The controller shall utilize low power large scale integration solid state components for high reliability.

6.4 Maintainability

The electronic controller shall be designed with the following maintainability objectives:

- a. "On condition" maintenance.
- b. Minimal test support equipment.
- c. Modular construction.
- d. Simple high reliability connections.
- e. Interchangeability of sub-assemblies.
- f. No special tools required.

6.5 Electrical Connectors

A minimum number of electrical connectors shall be used and shall conform to MIL-C-83723, Series 3, Threaded, Class H or R.

6.6 Propulsion System Fuel Subsystem

The entire fuel system downstream of the power section inlet connection, including the fuel flowmeter transmitter, will be integral with the power section.

The fuel piping upstream of the power section fuel pump inlet (including maintenance shutoff valve) and vapor educator system, if required, fuel pressure and temperature indication systems, and fuel drain system shall be included in the propulsion system.

The fuel system components shall be designed structurally and from a fuel resistant standpoint to use, alternately or in any combination, JP-4 per MIL-T-5624G, revised November 4, 1965, kerosene per D1655-65T (ASTM) dated June, 1965 and 115/130 aviation gasoline. The use of aviation gasoline is not planned, but inadvertent exposure of components to aviation gasoline shall not cause any damage.

It shall be possible to stop the flow of fuel to any power section with one valve, controlled by either the power section fire switch or a lever lock switch. The fuel shutoff valve installation shall provide protection for the valve in case of structural damage to the power section or nacelle.

A drain collection system shall be supplied. The requirement for overboard venting of drains shall be carefully controlled. Drain cans shall be checked at post-flight inspection, and drained during routine maintenance inspections.

The power section combustion chamber drain shall be vented overboard.

Accessory drive seal drains carrying unlike fluids may be grouped together except as stated above. Where practical, drains for "zero" leakage components (e.g., fuel and oil pressure transmitters) should be grouped separately from those for which leakage is more likely.

The drain-cans and all flammable fluid carrying drain lines shall be corrosion-resistant steel or fire proof hose.

All lines shall drain without trapping.

The first segment of seal drains from accessories shall be flexible to facilitate accessory removal.

Condensation drain holes shall be provided for trapped structural areas. Such trapped areas should be interconnected where possible within the structure and the number of required overboard drain holes held to a minimum.

All fluid drains shall be a minimum of 3/8" size.

6.7 Electrical

Package wiring shall be routed as open harness and shall be terminated at the firewall at which location it shall mate with receptacles installed on the pylon structure. Open wiring shall be routed to minimize the possibility of a broken wire contacting control cables actuating rods, fluid lines or tanks containing fluids. The wire harness shall be installed in a manner that will permit installation or removal of other components from the propulsion system. The harness shall be routed in a manner that will permit the same harness to be used on both left and right hand mounted propulsion systems. High-temperature wire shall be used. Resistance type temperature bulb wiring shall be installed in a manner that will minimize indicator errors caused by ground return currents. Ground terminal connections for these circuits shall not be shared with other systems.

Where wiring goes through cutouts in structure, a hard insulating material grommet or equivalent shall be used.

Wire clamping shall be provided at terminating ends to avoid breakage.

Where wire ducts are used, a suitable means shall be provided to prevent accumulation of fluids.

Wire for high temperature areas and fire detector (392 degrees Fahrenheit or higher), shall be to MIL-W-25038 or its equivalent.

No wire size smaller than 18 gauge shall be used.

Unused propulsion system wiring connectors, where provided for propulsion system interchangeability, shall terminate in dummy receptacles.

Wiring shall be isolated to the maximum degree possible from contact with adjacent harnessing, components, or power section casings, and shall be routed at higher elevations than fluid-carrying lines.

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